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28	

1 2	Acknowledgments
3	
4 5	EPA authors:
6 7 8 9	Benjamin DeAngelo, Jason Samenow, Jeremy Martinich, Doug Grano, Dina Kruger, William Irving, Lisa Hanle, Alan Cohn
10 11	EPA contributors and reviewers:
12 13 14 15 16 17	Melissa Weitz, Leif Hockstad, Steven Rose, Brooke Hemming, Sarah Garman, Rona Birnbaum, Paul Argyropoulos, Darrell Winner, Jason Burnett, Ann Wolverton, Al McGartland, Alan Carlin, John Davidson, Tim Benner, Carol Holmes, John Hannon, Robert Meyers, Jeanne Briskin, Jim Ketcham-Colwill, Andy Miller, Pamela Williams, Adam Daigneault, Kathryn Parker
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36 37 38	Other contributors:
39 40	Christine Teter, independent contractor for Stratus Consulting and Joel Smith, Stratus Consulting, assisted with editing and formatting.

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Executive Summary

 This document provides technical support for the endangerment analysis concerning greenhouse gas (GHG) emissions that may be addressed under the Clean Air Act. The primary GHGs of concern directly emitted by human activities include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6).

Global and U.S. Observed and Projected Effects of Elevated Greenhouse Gas Concentrations, Including Key Indicators of Climate Change

Greenhouse gases, once emitted, can remain in the atmosphere for decades to centuries, meaning that their concentrations become well-mixed throughout the global atmosphere regardless of emission origin. Greenhouse gases have a warming effect by trapping heat in the atmosphere that would otherwise escape to space.

The global atmospheric CO_2 concentration has increased about 35% from pre-industrial levels to 2005, and almost all of the increase is due to anthropogenic emissions. The global atmospheric concentration of CH_4 has increased by 148% since pre-industrial levels; and the N_2O concentration has increased 18%. The observed concentration increase in these gases can also be attributed primarily to anthropogenic emissions. The industrial fluorinated gases, HFCs, PFCs, and SF₆, have relatively low atmospheric concentrations but are increasing rapidly; these gases are entirely anthropogenic in origin. The current (year 2005) CO_2 concentration is 379 parts per million (ppm) and has recently been increasing by about 1.9 ppm per year.

Current ambient concentrations of CO₂ and other GHGs remain well below published thresholds for any direct adverse health effects, such as respiratory or toxic effects.

The global average net effect of the increase in atmospheric GHG concentrations, plus other human activities (e.g., land use change and aerosol emissions), on the global energy balance since 1750 has been one of warming. This total net radiative warming, referred to as forcing, is estimated to be +1.6 Watts per square meter (W/m²). The combined radiative forcing due to the cumulative (i.e., 1750 to 2005) increase in atmospheric concentrations of CO_2 , CH_4 , and N_2O is +2.30 W/m². The rate of increase in positive radiative forcing due to these three GHGs during the industrial era is very likely to have been unprecedented in more than 10,000 years. The positive radiative forcing due to CO_2 is the largest (+1.66 W/m²). Methane is the second largest source of positive radiative forcing (+0.48 W/m²). Nitrous oxide has a positive radiative forcing of +0.16 W/m².

Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. Global mean surface temperatures have risen by 0.74°C (1.3°F) over the last 100 years. The rate of warming over the last 50 years is almost double that over the last 100 years. Global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries. U.S. temperatures also warmed during the 20th and into the 21st century; temperatures are now approximately 0.56°C (1.0°F) warmer than at the start of the 20th century, with an increased rate of warming over the past 30 years.

Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations. Climate model simulations suggest natural forcings alone (e.g., changes in solar irradiance) cannot explain the observed warming. Likewise, North America's observed temperatures over the last century can only be reproduced using model simulations containing both natural and anthropogenic forcings.

Observations show that changes are occurring in the amount, intensity, frequency and type of precipitation. Over the contiguous U.S., total annual precipitation increased at an average rate of 6% per century from 1901-2005. It is likely that there have been increases in the number of heavy precipitation events within many land regions, even in those where there has been a reduction in total precipitation amount, consistent with a warming climate.

There is strong evidence that global sea level gradually rose in the 20th century and is currently rising at an increased rate. Nearly all of the Atlantic Ocean shows sea level rise during the past decade with the rate of rise reaching a maximum (over 2 mm per year) in a band along the U.S. east coast.

Widespread changes in extreme temperatures have been observed in the last 50 years across all world regions including the U.S. Cold days, cold nights, and frost have become less frequent, while hot days, hot nights, and heat waves have become more frequent.

Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases. Observations show that climate change is currently affecting the nation's ecosystems and services in significant ways.

Global and U.S. Projections of Future Climate Change

 The majority of future reference-case scenarios (assuming no explicit GHG mitigation actions beyond those already enacted) project an increase of global GHG emissions over the century, with climbing GHG concentrations and rising net positive radiative forcing. Carbon dioxide is expected to remain the dominant anthropogenic GHG over the course of the 21st century. The radiative forcing associated with the non-CO₂ GHGs is still significant and growing over time.

The range of projected ambient concentrations of CO_2 and other GHGs will remain well below published thresholds for any direct adverse health effects, such as respiratory or toxic effects.

Through about 2030, the global warming rate is affected little by different scenario assumptions or different model sensitivities. By mid-century, the choice of scenario becomes more important for the magnitude of the projected warming; about a third of that warming is projected to be due to climate change that is already committed. By the end of the century, projected average global warming (compared to average temperature around 1990) varies significantly by emissions scenario, ranging from 1.8 to 4.0°C (3.2 to 7.2°F), with an uncertainty range of 1.1 to 6.4°C (2.0 to 11.5°F), according to the Intergovernmental Panel on Climate Change (IPCC).

All of the U.S. is very likely to warm during this century, and most areas of the U.S. are expected to warm by more than the global average. The average warming in the U.S. is projected to exceed 2°C (3.6°F) by the end of the century by nearly all of the models assessed by IPCC, with 5 out of 21 models from IPCC projecting average warming in excess of 4°C (7.2°F). The largest warming is projected to occur in winter over northern parts of Alaska. In western, central and eastern regions of North America, the projected warming has less seasonal variation and is not as large, especially near the coast, consistent with less warming over the oceans. It is very likely that heat waves will become more intense, more frequent, and longer lasting in a future warm climate, whereas cold episodes are projected to decrease significantly.

Intensity of precipitation events is projected to increase in the U.S. and other regions of the world, increasing the risk of flooding, greater runoff and erosion, and thus the potential for adverse water

quality effects. Increases in the amount of precipitation are very likely in higher latitudes, while decreases are likely in most subtropical, more southern regions, continuing observed patterns in recent trends in observations. The mid-continental area is expected to experience drying during summer, indicating a greater risk of drought. It is likely that hurricanes will become more intense, with stronger peak winds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures.

By the end of the century, sea level is projected to rise between 0.18 and 0.59 meters relative to around 1990. These numbers represent the lowest and highest projections of the 5 to 95% ranges for all scenarios considered collectively and include neither uncertainty in carbon cycle feedbacks nor rapid dynamical changes in ice sheet flow. In all scenarios, the average rate of sea level rise during the 21^{st} century very likely exceeds the 1961 to 2003 average rate (1.8 \pm 0.5 mm per year). Sea ice is projected to shrink in the Arctic under all IPCC emission scenarios.

Global and U.S. Impacts Associated with Future Climate Change

The following highlights key issues and findings described in this report regarding potential impacts associated with climate change. Impacts in specific climate-sensitive systems and sectors in the U.S. are further synthesized in Table ES-1.

Risk increases with increases in both the rate and magnitude of climate change. Climate warming may increase the possibility of large, abrupt, and unwelcome regional or global climatic events (e.g., disintegration of the Greenland Ice Sheet or collapse of the West Antarctic Ice Sheet). The majority of the impacts literature assesses the effects of warming for climate sensitivities within the most likely range, not at the tails of the distribution. Consideration of outlier information is crucial for risk-management analysis even if potential impacts are of low probability or low confidence. The abrupt climate changes of the past are not fully explained yet, and climate models typically underestimate the size, speed, and extent of those changes. Hence, future abrupt changes cannot be predicted with confidence. Environmental changes that are more extreme or persistent than society's experience with natural climatic variability can lead to vulnerabilities, especially if the changes are not foreseen and/or if capacities for adaptation are limited.

Severe heat waves are projected to intensify in magnitude and duration over the portions of the U.S. where these events already occur, with likely increases in mortality and morbidity, especially among the elderly, young and frail. Climate change is projected to bring some benefits, such as fewer deaths from cold exposure. Ranges of vector-borne and tick-borne diseases in North America may expand but with modulation by public health measures and other factors (see Table ES-1).

The IPCC projects with virtual certainty declining air quality in U.S. and other world cities due to warmer and fewer cold days and nights and/or warmer/more frequent hot days and nights over most land areas. Climate change is expected to lead to increases in regional ozone pollution, with associated risks in respiratory infection, aggravation of asthma, and premature death. In addition to human health effects, tropospheric ozone has significant adverse effects on crop yields, pasture and forest growth and species composition. The directional effect of climate change on ambient particulate matter levels remains uncertain.

Moderate climate change in the early decades of the century is projected to increase aggregate yields of rainfed agriculture by 5-20% in the U.S., but with important variability among regions. However, as temperatures continue to rise, grain and oilseed crops will increasingly experience failure, especially if climate variability increases and precipitation lessens or becomes more variable. Recent studies indicate that climate change scenarios that include increased frequency of heat stress, droughts

and flooding events reduce crop yields and livestock productivity beyond the impacts due to changes in mean variables alone. Climate variability and change also modify the risks of pest and pathogen outbreaks. Climate change has the potential to adversely affect livestock productivity through thermal stress, changes in the nutritional value of grasses, and through extreme weather events. Cold-water fisheries will likely be negatively affected; warm-water fisheries will generally benefit; and the results for cool-water fisheries will be mixed, with gains in the northern and losses in the southern portions of ranges.

Disturbances like wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons. Overall forest growth in the U.S. will likely increase modestly (10-20%) as a result of extended growing seasons and elevated CO₂ over the next century, but with important spatial and temporal variation.

Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution. Sea level is rising along much of the U.S. coast, and the rate of change will increase in the future, exacerbating the impacts of progressive inundation, storm-surge flooding, and shoreline erosion. Storm impacts are likely to be more severe, especially along the Gulf and Atlantic coasts. Salt marshes, other coastal habitats, and dependent species are threatened by sea-level rise, fixed structures blocking landward migration, and changes in vegetation. Population growth and rising value of infrastructure in coastal areas increases vulnerability to climate variability and future climate change.

Sector	U.S. Impacts	Summary Assessment*
Health	Positive	The balance of positive and negative health impacts will vary from one
	Reduced death/illness from cold.	location to another, and will alter over time as temperatures continue to
	Negative	rise. Without increased investments in countermeasures, hot temperatures
	 Increased death/illness from heat waves. 	and extreme weather are likely to cause increased adverse health impacts
	• Deaths, injuries, infectious diseases, and stress-related disorders and other adverse effects from more frequent extreme weather.	from heat-related mortality, pollution, storm-related fatalities and injuries, and infectious diseases.
	• Expanded ranges of vector-borne and tick-borne diseases (but may be modulated by	
	public health measures).	
	Uncertain**	
	Increased respiratory illness from increases in pollen.	
Air Quality	Negative	Declining air quality in cities is a virtual certainty due to warmer and fewer
	Increased ozone pollution.	cold days and nights and/or warmer/more frequent hot days and nights over
	Uncertain	most land areas
	Climate change effects on particulate matter.	
Food	Positive	Rain-fed agriculture is projected to experience net benefits (5-20%
Production &	Extended growing season.	aggregate yield increase) with moderate climate change in the U.S.
Agriculture	• CO ₂ fertilization.	However, major challenges are projected for crops that are near the warm
	Benefits for warm water fisheries.	end of their suitable range or depend on highly utilized water resources.
	Negative	
	• Potential for increased frequency of heat stress, droughts and flooding events to affect crops and livestock.	
	 Increased risk of pest and pathogen outbreaks. 	
	Warming adversely impacts cold water fisheries.	
Forestry	Positive	Overall forest growth in the U.S. will likely increase modestly (10-20%) as
	• CO ₂ fertilization	a result of extended growing seasons and elevated CO ₂ over the next
	• Some tree types benefit from warming in cold climates.	century, but with important spatial and temporal variation. Disturbances
	Projected precipitation increases in some areas.	like wildfire and insect outbreaks are increasing and are likely to intensify
	Negative	in a warmer future with drier soils and longer growing seasons.
	Productivity losses for trees at the edge of their range.	
	Increase in wildfires and droughts.	
	Increases in disturbances from insects and diseases.	

Water	Positive	Climate change will constrain North America's over-allocated water
Resources	Precipitation increases enhance water availability in some areas.	resources, increasing competition among agricultural, municipal, industrial,
	Negative	and ecological uses.
	• Earlier melting and significant reductions in snowpack and less reliable supplies of water in the West.	
	Higher water temperatures, increased precipitation intensity, and longer periods of low flows exacerbate many forms of water pollution.	
	 Increases in drought adversely impact water supply and quality. 	
Sea Level	Negative	Sea level rise in the U.S. will exacerbate the impacts of progressive
Rise and	 Loss of wetlands from acceleration in sea level rise. 	inundation, storm-surge flooding, and shoreline erosion. Storm impacts are
Coastal	 Loss of waterfront property. 	likely to be more severe, especially along the Gulf and Atlantic coasts.
Resources	 Salt-water intrusion adversely affects water quality and some ecosystems. 	interference servere, especially along the Gall and Hamile coasts.
resources		
	• Superimposed on accelerated sea level rise, storm intensity, wave height, and storm	
	surge projections suggest more severe coastal flooding and erosion hazards.	
Energy,	Positive	Recent North American studies generally confirm earlier work showing a
Infrastructure	Decreased heating demand.	small net change in net demand for energy in buildings but a significant
and	Negative	increase in demand for electricity for space cooling.
Settlements	Increased cooling demand.	
	Extreme weather events could threaten coastal energy infrastructure and electricity	Climate change is likely to affect physical and institutional infrastructures;
	transmission and distribution infrastructures.	and will likely interact with and possibly exacerbate ongoing environmental
	• Infrastructure in parts of Alaska is projected to be at "moderate to high hazard" in the	change and environmental pressures in settlements particularly in Alaska
	mid-21 st century due to thawing permafrost.	where indigenous communities are facing major environmental and cultural
	• Changes in species' ranges and availability, access to these species present serious challenges to human health and food security, and possibly even the survival of some	impacts.
	indigenous cultures.	
	Uncertain	
	Potential impacts on energy production and distribution.	
Ecosystems	Positive	Over the 21st century, changes in climate will cause species to shift north
and Wildlife	At high latitudes, longer growing seasons lead to forest expansion into tundra ecosystems.	and to higher elevations and fundamentally rearrange North American ecosystems. Differential capacities for range shifts and constraints from
	Negative	development, habitat fragmentation, invasive species, and broken
	Many terrestrial, freshwater, and marine species near temperature thresholds are at	ecological connections will alter ecosystem structure, function, and
	risk of extinction.	services.
	Some organisms may not shift ranges fast enough to keep up with the pace of climate	
	change.	
	• Increases in wildfires and pest outbreaks are likely to limit carbon storage, facilitate invasive species, and disrupt ecosystem services.	
	 More frequent coral bleaching events and widespread mortality due to warming and ocean acidification due to elevated CO₂ concentrations. 	
*These summa	ry statements are from the IPCC Fourth Assessment Report and convey at least likely and/o	n high confidence findings (both of which convey at least a 66% probability

^{*}These summary statements are from the IPCC Fourth Assessment Report and convey at least likely and/or high confidence findings (both of which convey at least a 66% probability of occurrence).

^{**} Uncertain here denotes that either the direction of the impact is currently unknown or that the potential impact has not been adequately studied to date.

Climate change will constrain over-allocated water resources in the U.S., increasing competition among agricultural, municipal, industrial, and ecological uses. Rising temperatures will diminish snowpack and increase evaporation, affecting seasonal availability of water. Higher demand from economic development, agriculture and population growth will further limit surface and groundwater availability. In the Great Lakes and major river systems, lower levels are likely to exacerbate challenges relating to water quality, navigation, recreation, hydropower generation, water transfers, and bi-national relationships. Higher water temperatures, increased precipitation intensity, and longer periods of low flows can exacerbate many forms of water pollution and can impact ecosystems, human health, and water system reliability and operating costs. Decreased water supply and lower water levels are likely to exacerbate challenges relating to navigation in the U.S. Climate change impacts to water supply and quality can increase irrigation demand in dry regions and the aggravate non-point source water pollution problems in areas susceptible to intense rainfall events and flooding. The U.S. energy sector, which relies heavily on water for hydropower and cooling capacity, will be adversely impacted by changes to water supply and quality in reservoirs and other water bodies. Climate-induced environmental changes (e.g., loss of glaciers, reduced river discharge, reduced snow fall in winter) will affect park tourism, winter sport activities, inland water sports (e.g., fishing, rafting, boating), and other recreational uses dependent upon precipitation.

Climate change is likely to affect both U.S. energy use and energy production; physical infrastructures; institutional infrastructures; and will likely interact with and possibly exacerbate ongoing environmental change and environmental pressures in settlements, particularly in Alaska where indigenous communities are facing major environmental and cultural impacts.

Disturbances such as wildfire and insect outbreaks are increasing in the U.S. and are likely to intensify in a warmer future with drier soils and longer growing seasons. Although recent climate trends have increased vegetation growth, continuing increases in disturbances are likely to limit carbon storage, facilitate invasive species, and disrupt ecosystem services. Over the 21st century, changes in climate will cause species to shift north and to higher elevations and fundamentally rearrange U.S. ecosystems. Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections will alter ecosystem structure, function, and services.

Climate change impacts in certain regions of the world may exacerbate problems that raise humanitarian and national security issues for the U.S. The IPCC identifies the most vulnerable world regions as the Arctic, because of high rates of projected warming on natural systems; Africa, especially the sub-Saharan region, because of current low adaptive capacity as well as climate change; small islands, due to high exposure of population and infrastructure to risk of sea-level rise and increased storm surge; and Asian mega deltas, such as the Ganges-Brahmaputra and the Zhujiang, due to large populations and high exposure to sea level rise, storm surge and river flooding. Climate change has been described as a potential threat multiplier regarding national security issues.

Section 1

Introduction and Background

5 6

The purpose of this document is to provide scientific and technical support for an endangerment analysis regarding greenhouse gas (GHG) emissions under the Clean Air Act. This is a final internal EPA draft which has undergone initial EPA review as well as federal expert review (authors and reviewers are listed under Acknowledgments).

1(a) Scope and Approach of this Document

The primary GHGs of concern that are directly emitted by human activities in general are those reported in EPA's annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks* and include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF₆). The primary effect of these gases is their influence on the climate system by trapping heat in the atmosphere that would otherwise escape to space. This heating effect (referred to as radiative forcing) is very likely to be the cause of most of the observed global warming over the last 50 years. Global warming and climate change, in turn, can affect health, society and the environment. There also are some cases where these gases have other non-climate effects, some of which are direct while others are indirect. For example, elevated concentrations of CO₂ can increase ocean acidification and stimulate terrestrial plant growth, and CH₄ emissions can contribute to background levels of tropospheric ozone, a criteria pollutant. These effects may in turn be influenced by climate change in certain cases. Carbon dioxide and other GHGs can also have direct health effects but at concentrations far in excess of current or projected future ambient concentrations.

This document reviews a wide range of specific and quantifiable vulnerabilities, risks and impacts due to both effects induced by climate change and effects caused directly by the GHGs. Any known or expected benefits of elevated atmospheric concentrations of GHGs or of climate change are documented as well (i.e., impacts can mean either positive or negative consequences). The extent to which observed climate change can be attributed to anthropogenic GHG emissions is assessed. The term "climate change" in this document generally refers to climate change induced by human activities, including activities that emit GHGs. Future projections of climate change, based primarily on future scenarios of anthropogenic GHG emissions, are shown for the global and national scale.

The focus of the vulnerability, risk and impact assessment is primarily within the U.S. However, given the global nature of climate change, there is a brief review of potential international impacts. Greenhouse gases, once emitted, become well mixed in the atmosphere, meaning U.S. emissions can affect not only the U.S. population and environment but other regions of the world as well; likewise, emissions in other countries can affect the U.S. Furthermore, impacts in other regions of the world may have consequences that transcend national boundaries that raise concerns for the U.S.

The timeframe over which vulnerabilities, risks and impacts are considered is consistent with the timeframe over which GHGs, once emitted, have an effect on climate, which is decades to centuries for the primary GHGs of concern. Therefore, in addition to reviewing recent observations, this document generally considers the next several decades, the time period out to around 2100, and for certain impacts the time period beyond 2100.

Adaptation to climate change is a key focus area of the climate change research community. This document, however, does not focus on adaptation because adaptation is essentially a response to any known and/or perceived risks due to climate change. Likewise, mitigation measures to reduce GHGs,

- which could also reduce long-term risks, are not addressed. The purpose of this document is to review the
- 1 2 3 effects of climate change rather than society's response to climate change. Adaptation will be mentioned
- to the extent that the impacts projections themselves contain some embedded assumptions about future

adaptation. 1 4

¹ A brief overview of adaptation is provided in the Appendix.

Box 1.1, Peer review, publication and approval processes for IPCC, CCSP and NRC reports

Intergovernmental Panel on Climate Change

The World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988. It bases its assessment mainly on peer reviewed and published scientific/technical literature. IPCC has established rules and procedures for producing its assessment reports. Report outlines are agreed to by government representatives in consultation with the IPCC bureau. Lead authors are nominated by governments and are selected by the respective IPCC Working Groups on the basis of their scientific credentials and with due consideration for broad geographic representation. For Working Group I there were 152 coordinating lead authors, and for Working Group II 48 coordinating lead authors. Drafts prepared by the authors are subject to two rounds of review; the second round includes government review. For the IPCC Working Group I report, over 30,000 written comments were submitted by over 650 individual experts, governments and international organizations. For Working Group II there were 910 expert reviewers. Review Editors for each chapter are responsible for ensuring that all substantive government and expert review comments receive appropriate consideration. IPCC documents how every comment is addressed. Each Summary for Policymakers is approved line-by-line, and the underlying chapters are then accepted, by government delegations in formal plenary sessions. Further information about IPCC's principles and procedures can be found at: http://www.ipcc.ch/about/procd.htm.

U.S. Climate Change Science Program

The CCSP has identified 21 synthesis and assessment products (SAPs) that address the highest priorities for U.S. climate change research, observation and decision-support needs. Not all of these assessment products have been completed in time for use in this document. Different agencies have been designated the lead for different SAPs; EPA is the designated lead for three of the six SAPs addressing impacts and adaptation. For each SAP, there is first a prospectus that provides an outline, the proposed authors and process for completing the SAP; this goes through two stages of expert, interagency and public review. Authors produce a first draft which goes through expert review; a second draft is posted for public review. The designated lead agency ensures that the third draft complies with the Information Quality Act. Finally the SAP is submitted to the National Science and Technology Council (NSTC), a Cabinet-level council that coordinates science and technology research across the Federal government, for approval. Further information about the clearance and review procedures for the CCSP SAPs can be found at: http://www.climatescience.gov/Library/sap/sap-guidelines-clarification-aug2007.htm.

National Research Council of the U.S. National Academy of Sciences

The National Research Council (NRC) is part of the National Academies, which also comprise the National Academy of Sciences, National Academy of Engineering and Institute of Medicine. They are private, nonprofit institutions that provide science, technology and health policy advice under a congressional charter. The NRC has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public and the scientific and engineering communities. Federal agencies are the primary financial sponsors of the Academies' work. The Academies provide independent advice; the external sponsors have no control over the conduct of a study once the statement of task and budget are finalized. The NRC 2001 study, Climate Change Science: An Analysis of Some Key Questions, originated from a White House request. The NRC 2001 study, Global Air Quality: An Imperative for Long-Term Observational Strategies, was supported by EPA and NASA. The NRC 2004 study, Air Quality Management in the United States, was supported by EPA. The NRC 2005 study, Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties, was in response to a CCSP request, and supported by NOAA. The NRC 2006 study, Surface Temperature Reconstructions for the Last 2,000 Years, was requested by the Science Committee of the U.S. House of Representatives. Each NRC report is authored by its own committee of experts, reviewed by outside experts, and approved by the Governing Board of the NRC.

Uncertainties and confidence levels associated with the scientific conclusions and findings in this document are reported, to the extent that such information was provided in the original scientific reports upon which this document is based.

1(b) Data and Scientific Findings Considered by EPA

This document relies most heavily on existing, and in most cases very recent, synthesis reports of climate change science and potential impacts, which have gone through their own peer-review processes including review by the U.S. Government. The information in this document has been developed and prepared in a manner that is consistent with EPA's *Guidelines for Ensuring and Maximizing the Quality, Objectivity, Utility and Integrity of Information Disseminated by the Environmental Protection Agency.* In addition to its reliance on existing and primarily recent synthesis reports from the peer reviewed literature, it also underwent a technical review by 12 federal climate change experts, internal EPA review, and interagency review.

These core reference (Table 1.1) documents include the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Synthesis and Assessment Products of the U.S. Climate Change Science Program (CCSP) completed and publically released to date, National Research Council (NRC) reports under the U.S. National Academy of Sciences (NAS), and the EPA annual report on U.S. greenhouse gas emission inventories.

EPA is relying most heavily on these synthesis reports because they 1) are very recent and represent the current state of knowledge on climate change science, vulnerabilities and potential impacts; 2) have assessed numerous individual studies in order to draw general conclusions about the state of science; 3)have been reviewed and formally accepted by, commissioned by, or in some cases authored by, U.S. government agencies and individual government scientists and provide EPA with assurances that this material has been well vetted by both the climate change research community and by the U.S. government; and 4) in many cases, they reflect and convey the consensus conclusions of expert authors. Box 1.1 describes the peer review and publication approval processes of IPCC, CCSP and NRC reports. Box 1.2 provides guidance for the reader about how this document references different chapters of the IPCC reports. Box 1.3 describes the lexicon used by IPCC to communicate uncertainty and confidence levels associated with the most important IPCC findings; this document employs the same lexicon when referencing IPCC statements.

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Table 1.1, Core references relied upon most heavily in this document.		
Science body and author	Short Title and Year of Publication	
IPCC	Working Group I: The Physical Science Basis (2007)	
IPCC	Working Group II: Impacts, Adaptation and Vulnerability (2007)	
IPCC	Working Group III: Mitigation of Climate Change (2007)	
CCSP	SAP 1.1: Temperature Trends in the Lower Atmosphere (2006)	
CCSP	SAP 2.1: Scenarios of GHG Emissions and Atmospheric Concentrations (2007)	
CCSP	SAP 4.3: Effects on Agriculture, Land Resources, Water Resources, and Biodiversity (2008)	
CCSP	SAP 4.5: Effects on Energy Production and Use (2007)	
CCSP	SAP 4.7: Gulf Coast Study (2008)	
CENR	Assessment of the Effects of Global Change on the United States (2008)	
NRC	Climate Change Science: Analysis of Some Key Questions (2001)	
NRC	Radiative Forcing of Climate Change (2005)	
NRC	Surface Temperature Reconstructions for the Last 2,000 Years (2006)	
NRC	Potential Impacts of Climate Change on U.S. Transportation (2008)	
EPA	Inventory of U.S. Greenhouse Gas Emissions and Sinks (2007)	
ACIA	Arctic Climate Impact Assessment (2004)	

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DRAFT 6/21/08 SIXTH ORDER DRAFT, DO NOT CIRCULATE OR CITE

The IPCC Fourth Assessment Report consists of three volumes: Working Group I addresses the physical science of climate change; Working Group II addresses impacts, vulnerabilities and adaptation; and Working Group III addresses mitigation (i.e., emission reduction) measures. These IPCC assessments are generally global in scope but provide information at the country and regional level as well. The Working Group II volume contains individual chapters devoted to the key climate change impact sectors, which are also addressed in this document (e.g., human health, agriculture, water resources, etc.), as well as chapters devoted to key regions. This document relies heavily on the North America chapter of the IPCC Working Group II report, though this chapter may not provide as much regional detail within the U.S. as did the 2000 report, Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change (NAST, 2000).

Box 1.3: Communication of uncertainty in the IPCC Fourth Assessment Report

A set of terms to describe uncertainties in current knowledge is common to all parts of the IPCC Fourth Assessment Report, based on the *Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties* (http://www.ipcc.ch/activity/uncertaintyguidancenote.pdf), produced by the IPCC in July 2005. Any use of these terms in association with IPCC statements in this Endangerment document carries the same meaning as originally intended in the IPCC Fourth Assessment Report.

Description of confidence

On the basis of a comprehensive reading of the literature and their expert judgment, authors have assigned a confidence level to major statements on the basis of their assessment of current knowledge, as follows:

Very high confidence At least 9 out of 10 chance of being correct

High confidence About 8 out of 10 chance
Medium confidence About 5 out of 10 chance
Low confidence About 2 out of 10 chance
Very low confidence Less than a 1 out of 10 chance

Description of likelihood

Likelihood refers to a probabilistic assessment of some well defined outcome having occurred or occurring in the future, and may be based on quantitative analysis or an elicitation of expert views. When authors evaluate the likelihood of certain outcomes, the associated meanings are:

Virtually certain >99% probability of occurrence

Very likely 90 to 99% probability
Likely 66 to 90% probability
About as likely as not 33 to 66% probability
Unlikely 10 to 33% probability
Very unlikely 1 to 10% probability
Exceptionally unlikely <1% probability

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In some cases, this document references other reports and studies in addition to the core references of IPCC, CCSP, NRC, and, for greenhouse gas emissions, EPA. This is usually the case where IPCC, CCSP and NRC reports do not explicitly provide the regional or state-level detail for certain vulnerabilities and potential impacts, or where very recent and significant studies have been published that were not included by the IPCC and CCSP synthesis reports due to publication cut-off dates.

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Because IPCC, CCSP and NRC are assessment reports in which a number of individual studies are synthesized in order to draw more general conclusions, this document often cites those individual studies

that tended to be very influential in the more general findings of IPCC, CCSP; however, every effort is made to make it clear when an individual reference was incorporated into one of the broader assessments. Full citations of all references are listed at the end of this document.

1(c) Roadmap for this Document

The remainder of this document is structured as follows:

- Part II, Section 2 describes sources of U.S. and global GHG emissions. How anthropogenic GHG emissions have contributed to changes in global atmospheric concentrations of GHGs is also described.
- Part III, Sections 3 6 describe the effects of elevated concentrations of GHGs including any direct health and environmental effects; the heating or radiative forcing effects on the climate system; observed climate change (e.g., changes in temperature, precipitation and sea level rise) for the U.S. and for the globe; recent conclusions about the extent to which observed climate change can be attributed to the elevated levels of GHG concentrations; and summarize future projections of climate change—driven primarily by scenarios of anthropogenic GHG emissions—for the remainder of this century.
- Part IV, Sections 7 14 review recent findings for the broad range of observed and projected vulnerabilities, risks and impacts for human health, society and the environment within the U.S. due to climate change. The specific sectors and systems include:
 - o Human health (7)
 - o Air Quality (8)
 - o Food Production and Agriculture (9)
 - o Forestry (10)
 - o Water Resources (11)
 - o Coastal Areas (12)
 - o Energy, Infrastructure and Settlements (13)
 - o Ecosystems and Wildlife (14)
- Part V, Section 15 briefly addresses some key international impacts that may occur due to climate change, with a view towards how some of these impacts may in turn affect the U.S.
 - o International Impacts (15)

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Section 2

Greenhouse Gas Emissions and Concentrations

This section first describes current U.S. and global anthropogenic greenhouse gas (GHG) emissions. Future GHG emission scenarios are described in Part III, Section 6, however, these scenarios primarily focus on global emissions, rather than detailing individual U.S. sources. This section then focuses on historic and current global GHG atmospheric concentrations.

2(a) U.S. and global greenhouse gas emissions

To track the national trend in emissions and carbon removals since 1990, EPA develops the official U.S. GHG inventory each year. In accordance with Article 4.1 of the United Nations Framework Convention on Climate Change (UNFCCC), the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* includes emissions and removals of carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆) resulting from anthropogenic activities in the U.S. Total emissions are presented in teragrams² (Tg) of CO₂ equivalent (TgCO₂eq), consistent with Intergovernmental Panel on Climate Change (IPCC) inventory guidelines. To determine the CO₂ equivalency of different GHGs, in order to sum and compare different GHGs, emissions of each gas are multiplied by its global warming potential (GWP), a factor which relates it to CO₂ in its ability to trap heat in the atmosphere over a certain timeframe. Box 2.1 provides more information about GWPs and the GWP values used in this section of the report.

Box 2.1: Global Warming Potentials used in this document

In accordance with UNFCCC reporting procedures, the U.S. quantifies GHG emissions using the 100-year time frame values for GWPs established in the IPCC Second Assessment Report (SAR) (IPCC, 1996). The GWP index is defined as the cumulative radiative forcing between the present and some chosen later time horizon (100 years) caused by a unit mass of gas emitted now. All GWPs are expressed relative to a reference gas, CO_2 , which is assigned a GWP = 1. Estimation of the GWPs requires knowledge of the fate of the emitted gas and the radiative forcing due to the amount remaining in the atmosphere. To estimate the CO_2 equivalency of a non- CO_2 GHG, the appropriate GWP of that gas is multiplied by the amount of the gas emitted.

100-year GWPs	
CO_2	1
CH_4	21
N_2O	310
HFCs	140 to 6,300 (depende
PFCs	6 500 to 9 200 (depen

 $\begin{array}{ll} \text{HFCs} & 140 \text{ to } 6{,}300 \text{ (depending on type of HFC)} \\ \text{PFCs} & 6{,}500 \text{ to } 9{,}200 \text{ (depending on type of PFC)} \\ \text{SF}_6 & 23{,}900 \end{array}$

The GWP for CH₄ includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. These GWP values have been updated twice, in the IPCC third (TAR

ozone and stratospheric water vapor. These GWP values have been updated twice, in the IPCC third (TAR 2001) and fourth assessment reports (AR4 2007). The use of TAR values for GWP, instead of SAR values, increases the overall U.S. GHG inventory for 2005 by 0.4% (EPA, 2007).

The national inventory totals used in this report for the US (and other countries) are gross emissions, which include greenhouse gas emissions from the electricity, industrial, commercial, residential and

 $^{^2}$ 1 teragram (Tg) = 1 million metric tons. 1 metric ton = 1,000 kg = 1.102 short tons = 2,205 lbs.

agriculture sectors. Emissions and sequestration occurring in the land-use, land-use change and forestry sector (e.g., forests, soil carbon etc.) are not included in gross national totals, but are reported under net emission totals (sources and sinks), according to international practice. In the U.S., this sector is a significant sink, while in some developing countries it is a significant net source of emissions.

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Also excluded from emission totals in this report are bunker fuels (fuels used for international transport). According to UNFCCC reporting guidelines, emissions from the consumption of these fuels should be reported separately, and not included in national emission totals, as there exists no agreed upon international formula for allocation between countries.

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The most recent inventory was published in 2007 and includes annual data for the years 1990-2005.

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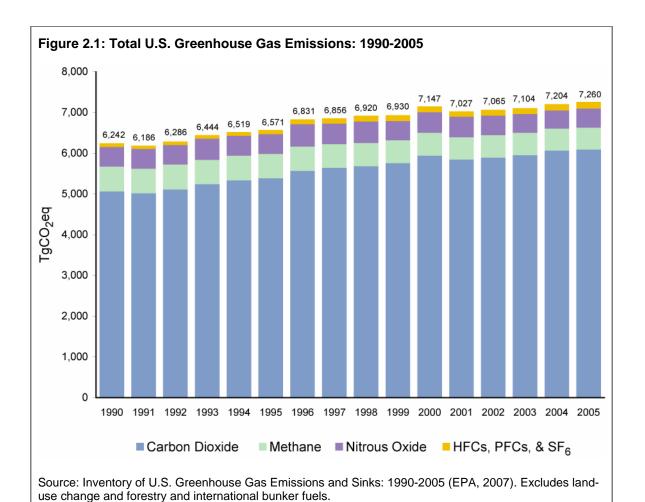
U.S. Greenhouse Gas Emissions

In 2005, U.S. GHG emissions were 7,260.4 TgCO₂eq (see Figure 2.1).³ The dominant gas emitted is CO₂, 14 15 mostly from fossil fuel combustion (83.9%) (EPA, 2007). Weighted by GWP, CH₄ is the second largest 16 component of emissions, followed by N₂O, and the high-GWP fluorinated gases (HFCs, PFCs, and SF₆). 17 Electricity generation (2,429.8 TgCO₂eq) is the largest emitting sector, followed by transportation 18 (2,008.9 TgCO₂eq) and industry (1,352.8 TgCO₂eq) (EPA, 2007) (Figure 2.2). Agriculture and the 19 commercial and residential sectors emit 595.4 TgCO₂eq, 431.4 TgCO₂eq, and 380.7 TgCO₂eq, 20 respectively (EPA, 2007). Removals of carbon through land use, land-use change and forestry activities 21 are not included in Figure 2.2, but are significant; net sequestration is estimated to be 828.5 TgCO₂eq in 22 2005, offsetting 11.4% of total emissions (EPA, 2007).

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³ Per UNFCCC reporting requirements, the U.S. reports its annual emissions in gigagrams (Gg) with two significant digits (http://unfccc.int/files/national_reports/annex_i_ghg_inventories/national_inventories_submissions/application/x-zip-compressed/usa_2007_crf_11apr.zip). For ease of communication of the findings, the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* report presents total emissions in Tg with one significant digit.



by 1,018.4 TgCO₂eq, or 16.3% between 1990 and 2005 (see Figure 2.1) (EPA, 2007). Historically, changes in fossil fuel consumption have been the dominant factor affecting U.S. emission trends. The fundamental factors driving this trend include a generally growing domestic economy over the last 15 years, leading to growth overall emissions from electricity generation (increase 30.7%) and transportation activities (increase

31.9%) (EPA, 2007). Over

the same time period,

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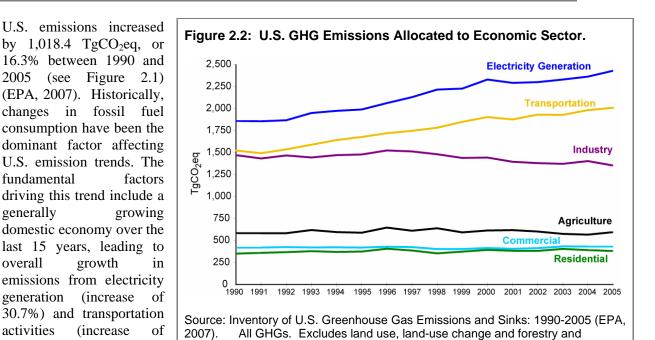
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international bunker fuels.

industrial emissions decreased by 8.0%, while emissions increased in the residential (8.4%), commercial (3.3%), and agriculture (1.7%) sectors (Figure 2.2) (EPA, 2007).

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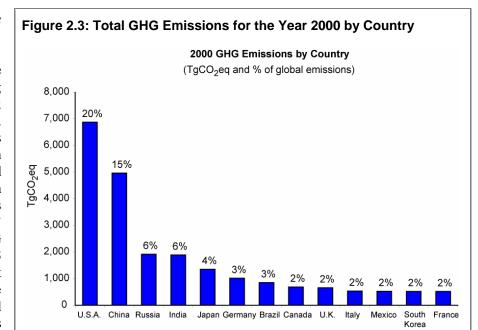
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Global Greenhouse Gas Emissions

Total global emissions are calculated by summing emissions of the six greenhouse gases, by country. The World Resources Institute compiles data from recognized national and international data sources in Climate its Analysis (CAIT).4 **Indicators** Tool Globally, total GHG emissions 33,713 were TgCO₂eq in 2000, the most recent year for which data are available for all countries and all gases (WRI, 2007).⁵ This global total for the year 2000 represents an increase of about 10% from the 1990 global GHG emission total of 30,540 TgCO₂eq (WRI, 2007). Excluding land use,



Source: WRI Climate Analysis and Indicators Tool. Available at http://cait.wri.org/. Excludes land use, land-use change and forestry, and international bunker fuels. More recent emissions data are available for the U.S. and other individual countries, but 2000 is the most recent year for which data for all countries and all gases are available. Data accessed June 30, 2007.

land-use change, and forestry, U.S. emissions were 20% of the total year 2000 global emissions, (see Figure 2.3) (WRI, 2007). Note that, with one important exception, GHG emissions for more recent years would be largely similar to those shown in Figure 2.3. Emissions from China have increased at a rapid rate during the last several years and China's CO₂ emissions are now closer to those of the U.S.⁶

2(b) Historic and current global greenhouse gas concentrations

Greenhouse gas concentrations in the atmosphere vary over very long time scales in response to natural influences such as geologic activity and temperature change associated with ice age cycles, but ice core data show nearly constant concentrations of CO_2 , CH_4 and N_2O over more than 10,000 years prior to the industrial revolution. However, since the industrial revolution, anthropogenic GHG emissions have resulted in substantial increases in the concentrations of GHGs in the atmosphere (IPCC 2007d; NRC, 2001).

Carbon dioxide (CO₂)

⁴ Primary data sources referenced in CAIT include the U.S. Department of Energy's Carbon Dioxide Information Analysis Center, the U.S. Environmental Protection Agency, the International Energy Agency and the National Institute for Public Health and the Environment, an internationally recognized source of non-CO₂ data.

⁵ Source: WRI Climate Analysis and Indicators Tool. Available at http://cait.wri.org/.

⁶ See WRI CAIT version 5.0 for 2004 CO₂ emissions data.

Carbon dioxide concentrations have increased substantially from pre-industrial levels (Figure 2.4). The IPCC reports the following long term trends in the carbon dioxide concentrations (Forster, P. et al., 2007^7):

• The CO₂ concentration has increased about 35% from a pre-industrial value of about 280 parts per million (ppm) to 379 ppm (which is about 0.038% of the atmosphere by volume) in 2005.

The atmospheric concentration of CO₂ in 2005 exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores.
 The annual carbon dioxide concentration growth rate was larger during the last 10 years (1995–

 • The annual carbon dioxide concentration growth rate was larger during the last 10 years (1995–2005 average: 1.9 ppm per year), than it has been since the beginning of continuous direct atmospheric measurements (1960–2005 average: 1.4 ppm per year) although there is year-to-year variability.

Almost all of the increase in the CO_2 concentration during the Industrial Era is due to anthropogenic emissions (Forster et al., 2007). Since the 1980s, about half of the anthropogenic emissions have been taken up by the terrestrial biosphere and the oceans, but observations demonstrate that these processes cannot remove all of the extra flux due to human activities. About half of the anthropogenic emissions have remained in the atmosphere (Forster et al., 2007).

⁷ Forster, P. et al., 2007 citation refers to Chapter 2, "Changes in Atmospheric Constituents and in Radiative Forcing" in IPCC's 2007 Fourth Assessment Report, Working Group I.

Methane (CH₄)

Methane concentrations have also risen substantially (Figure 2.4). The following trends in atmospheric methane have been observed according to the IPCC (Forster et al., 2007):

- The global atmospheric concentration of methane has increased from a pre-industrial value of about 715 parts per billion (ppb) to 1732 ppb in the early 1990s, and was 1774 ppb in 2005 a 148% increase from pre-industrial levels.
- The atmospheric concentration of methane in 2005 exceeds by far the natural range of the last 650,000 years (320 to 790 ppb) as determined from ice cores.
- Growth rates have declined since the early 1990s, consistent with total emissions (sum of anthropogenic and natural sources) being nearly constant during this period.

The observed increase in methane concentration is very likely due to anthropogenic activities, predominantly agriculture and fossil fuel use, but relative contributions from different source types are not well determined (Forster et al., 2007).

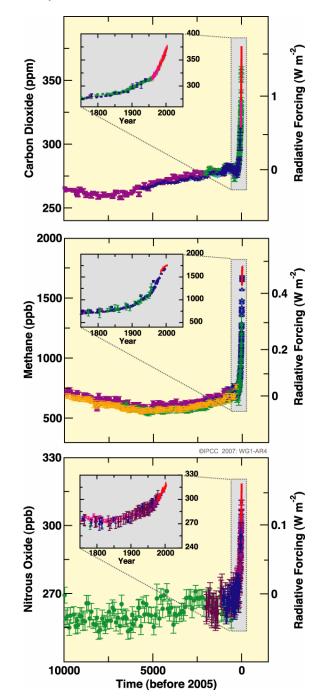
Nitrous Oxide (N_2O)

The N₂O concentration has increased 18% from its pre-industrial value to 319 ppb in 2005 (Figure 2.4) (Forster, P. et al., 2007). The concentration has increased linearly by about 0.8 ppb yr⁻¹ over the past few decades and is due primarily to human activities, particularly agriculture and associated land use change (Forster et al., 2007). Ice core data show that the atmospheric concentration of N₂O varied by less than about 10 ppb for 11,500 years before the onset of the industrial period (Forster et al., 2007).

Fluorinated Gases

Cholorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are greenhouse gases that are entirely anthropogenic in origin. Emissions of these

Figure 2.4: Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years



Source: IPCC (2007d). Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colors for different studies) and atmospheric samples (red lines). The corresponding radiative forcings (discussed in Section 2(e)) are shown on the right hand axes of the large panels.

gases have decreased due to their phase-out under the Montreal Protocol, and the atmospheric concentrations of CFC-11 and CFC-113 are now decreasing due to natural removal processes (Forster et al., 2007). Ice core and in situ data confirm that industrial sources are the cause of observed atmospheric increases in CFCs and HCFCs (Forster et al., 2007).

Industrial fluorinated gases that serve as substitutes for CFCs and HCFCs (hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF₆)) have relatively low atmospheric concentrations but are increasing rapidly. These are also entirely anthropogenic in origin (Forster et al., 2007).

Ozone (O_3)

Tropospheric ozone is a short-lived greenhouse gas produced by chemical reactions of precursor species in the atmosphere and with large spatial and temporal variability. It is estimated that ozone has increased by about 36% since the pre-industrial era, although substantial variations exist for regions and overall trends (Forster et al., 2007). Relative to the other greenhouse gases, there is less confidence in reproducing the changes in ozone associated with large changes in emissions or climate, and in the simulation of observed long-term trends in ozone concentrations over the 20th century (Forster et al., 2007).

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Section 3

Direct Effects of Elevated Greenhouse Gas Concentrations

This section briefly addresses some direct effects associated with GHGs, but focuses primarily on the more significant effects associated with GHGs, which is their heat-trapping ability (referred to as radiative forcing) that results in to climate change. Observed climate change, including changes in temperature, precipitation, sea level rise, for the globe and the U.S. is reviewed. Observed changes in climate-sensitive physical and biological systems are also addressed, as well as observed trends in extreme events.

Sections 7 to 15 provide more specific information on the sectoral implications of both the observed changes described here and the projected changes described in Section 5.

3(a) Carbon dioxide (CO₂)

Carbon dioxide and other GHGs can have direct effects that are independent of their radiative forcing on climate (the primary effect discussed throughout this document).

The direct effects of high CO₂ concentrations on human health were assessed in the EPA (2000) report, *Carbon Dioxide as a Fire Suppressant: Examining the Risks*, and have also been reviewed by the IPCC (2005) *Special Report on Carbon Dioxide Capture and Storage*. At concentrations above about 2%, CO₂ has a strong effect on respiratory physiology and at concentrations above 7–10%, it can cause unconsciousness and death (IPCC, 2005). Exposure studies have not revealed any adverse health effect of chronic exposure to concentrations below 1%. At concentrations greater than 17 percent, loss of controlled and purposeful activity, unconsciousness, convulsions, coma, and death occur within 1 minute of initial inhalation of CO₂ (OSHA, 1989; CCOHS, 1990; Dalgaard et al., 1972; CATAMA, 1953; Lambertsen, 1971). But CO₂ is a physiologically active gas and is a normal component of blood gases (EPA, 2000). Acute CO₂ exposure of up to 1 percent and 1.5 percent by volume is tolerated quite comfortably (EPA, 2000b).

The ambient concentration of CO_2 in the atmosphere is presently about 0.038 percent by volume (or 380 ppm). Projected increases in CO_2 concentrations from anthropogenic emissions range from 41 to 158 percent above present levels (of about 380ppm) or 535 to 983 parts per million (ppm) by 2100 (Meehl et al., 2007) (see Section 5). Such increases would result in atmospheric CO_2 concentrations of 0.054 to 0.098 percent by volume in 2100, which is well below published thresholds for adverse health effects.

Carbon dioxide can have stimulatory or fertilization effect on plant growth. There is debate and uncertainty about the sensitivity of crop yields to the direct effects of elevated CO₂ levels. However, IPCC (Easterling et al., 2007) concluded that elevated CO₂ levels are expected to result in small beneficial impacts on crop yields. The IPCC confirmed the general conclusions from its previous Third Assessment Report in 2001. Experimental research on crop responses to elevated CO₂ through the FACE (Free Air CO₂ Enrichment)⁸ experiments indicate that, at ambient CO₂ concentrations of 550 ppm (approximately double the concentration from pre-industrial times) crop yields increase under unstressed conditions by 10-25% for C3 crops, and by 0-10% for C4 crops (medium confidence)⁹. Crop model simulations under elevated CO₂ are consistent with these ranges (high confidence) (Easterling et al., 2007). Globally and in

⁸ http://www.bnl.gov/face/

⁹ C3 and C4 refer to different carbon fixation pathways in plants during photosynthesis. C3 is the most common pathway, and C3 crops (e.g., wheat, soybeans and rice) are more responsive than C4 crops such as maize.

the U.S., high temperatures and ozone exposure, however, can significantly limit the direct stimulatory CO₂ response (see also Section 8 on Air Quality and Section 9 on Food Production and Agriculture).

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Elevated CO₂ has raised an issue about forage quality for livestock. Elevated CO₂ can increase the carbon to nitrogen ratio in forages and thus reduce the nutritional value of those grasses and thus affect animal weight and performance. The decline under elevated CO₂ of C4 grasses, however, which are less nutritious than C3 grasses, may compensate for the reduced protein. Yet the opposite is expected under associated temperature increases.

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At much higher ambient CO₂ concentrations, such those areas exposed to natural CO₂ outgassing due to volcanic activity, the main characteristic of long-term elevated CO₂ zones at the surface is the lack of vegetation (IPCC, 2005). New CO₂ releases into vegetated areas cause noticeable die-off. In those areas where significant impacts to vegetation have occurred, CO₂ makes up about 20-95% of the soil gas, whereas normal soil gas usually contains about 0.2-4% CO₂. Carbon dioxide concentrations above 5% may be dangerous for vegetation and as concentration approach 20%, CO₂ becomes phytotoxic. Carbon dioxide can cause death of plants through 'root anoxia', together with low oxygen concentration (IPCC, 2005).

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Regarding oceanic ecosystems, according to IPCC (Fischlin et al., 2007), ocean acidification due to the direct effects of elevated CO₂ concentrations will impair a wide range of planktonic and other marine organisms that use aragonite to make their shells or skeletons. These impacts could result in potentially severe ecological changes to tropical and coldwater marine ecosystems where carbonate-based phytoplankton and corals are the foundation for the trophic system (Schneider et al., 2007). These CO₂ effects will also interact with the effects of temperature change (see Section 14 on Ecosystems and Wildlife).

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3(b) Methane (CH₄)

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Methane is flammable or explosive at concentrations of 5% to 15% by volume (50,000 to 150,000 ppm) of air (NIOSH, 1994; NRC, 2000). At high enough concentrations, CH₄ is also a simple asphyxiant, capable of displacing enough oxygen to cause death by suffocation. Threshold limit values are not specified because the limiting factor is the available oxygen (NRC, 2000). Atmospheres with oxygen concentrations below 19.5 percent can have adverse physiological effects, and atmospheres with less than 16 percent oxygen can become life threatening (MSHA, 2007). Methane displaces oxygen to 18% in air when present at 14% (140,000 ppm).

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When oxygen is readily available, CH₄ has little toxic effect (NRC, 2000). In assessing emergency exposure limits for CH₄, the NRC (2000) determined that an exposure limit that presents an explosion hazard cannot be recommended, even if it is well below a concentration that would produce toxicity. As such, it recommended an exposure limit of 5000 ppm for methane (NRC, 2000). The National Institute for Occupational Health Safety (NIOSH, 1994) established a threshold limit value (TLV) for methane at 1,000 ppm.

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44 The current atmospheric concentration of CH₄ is 1.77 ppm. The projected CH₄ concentration in 2100 ranges from 1.46 ppm to 3.39 ppm by 2100, well below any recommended exposure limits (Meehl et al., 46 2007).

47 3(c) Nitrous Oxide (N₂O)

- 48 Nitrous oxide is an asphyxiant at high concentrations. At lower concentrations, exposure causes central 49 nervous system, cardiovascular, hepatic (pertaining to the liver), hematopoietic (pertaining to the
- 50 formation of blood or blood cells), and reproductive effects in humans (Hathaway et al., 1991). At a

- 1 concentration of 50 to 67 percent (500,000 to 670,000 ppm) nitrous oxide is used to induce anesthesia in
- 2 humans (Rom, 1992).
- 3 NIOSH has established a recommended exposure limit (REL) for nitrous oxide of 25 ppm as a time-
- 4 weighted average (TWA) for the duration of the exposure (NIOSH, 1992). The American Conference of
- 5 Governmental Industrial Hygienists (ACGIH) has assigned nitrous oxide a TLV of 50 ppm as a TWA for
- 6 a normal 8-hour workday and a 40-hour workweek (ACGIH, 1994).
- 7 The NIOSH limit is based on the risk of reproductive system effects and decreases in audiovisual
- 8 performance (NIOSH, 1992). The ACGIH limit is based on the risk of reproductive, hematological
- 9 (related to the study of the nature, function, and diseases of the blood and of blood-forming organs), and
- 10 nervous system effects (ACGIH 1991)
- 11 The current atmospheric concentration of nitrous oxide was 0.32 ppm. The projected nitrous oxide
- 12 concentration in 2100 ranges from 0.36 to 0.46 ppm in 2100, well below any exposure limits (Meehl et
- 13 al., 2007).

14 3(d) Fluorinated Gases (HFCs, PFCs, SF₆)

- Most fluorinated gases emitted from anthropogenic activities are released in very small quantities relative
- 16 to established thresholds for adverse health outcomes from exposure. The health effects of exposure to
- one illustrative HFC gas, one illustrative HCFC gas and SF₆ are given in the context of their current
- 18 atmospheric concentration. Chlorofluorocarbons are not included in this discussion given their phaseout
- 19 under the Montreal Protocol.
- 20 The NRC (1996) recommended a 1-hr emergency exposure guidance level (EEGL) of 4,000 ppm for
- 21 HFC-134a. This recommendation was based on a no-observed-adverse-effect level of 40,000 ppm in
- cardiac-sensitization tests of male beagles (NRC, 1996). It recommended 24-hr EEGL of 1,000 ppm
- based on the fetotoxicity effects (slight retardation of skeletal ossification) observed in rats exposed to
- 24 HFC-134a. Finally, it recommended a 90-day CEGL of 900 ppm based on a 2-year chronic toxicity study
- conducted in male rats exposed to HFC-134a at different concentrations for 6 hours/day, 5 days/week.
- 26 The atmospheric concentration of HFC 134a in 2003 was in the range of 26 to 31 parts per trillion
- according to IPCC/TEAP (2005), many orders of magnitude below EEGLs.
- For HCFC-123, the end points of pharmacological or adverse effects considered for establishing an EEGL
- are cardiac sensitization, anesthesia or CNS-related effects, malignant hyperthermia, and hepatotoxicity.
- 30 According to the NRC (1996), concentration required to produce cardiac sensitization in 50% of the
- animals) for HCFC-123 was determined in dog studies to be 1.9% (19,000 ppm) for a 5-minute exposure.
- 32 The NRC recommended that 1,900 ppm (19,000 ppm divided by an uncertainty factor of 10 for
- interspecies variability) should be considered the human no-observed-effect level for a 1-min exposure to
- 34 HCFC-123 on the basis of the dog cardiac-sensitization model. The concentration of HCFC-123 in 1996
- was 0.03 parts per trillion according to IPCC/TEAP (2005), many orders of magnitude below the
- 36 established effect level.

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- 38 Sulfur hexafluoride (SF₆) is a relatively non-toxic gas but an asphyxiant at high concentrations. The
- NIOSH, 1997) recommended exposure limit is 1,000 ppm. The SF₆ concentration in 2003 was around 5
- 40 parts per trillion according to IPCC/TEAP (2005), many orders of magnitude below the exposure limit.

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Section 4

4(a) Radiative forcing due to greenhouse gases and other factors

Radiative Forcing and Observed Climate Change

This section describes radiative forcing and the factors that contribute to it. Radiative forcing is a measure of the change that a factor causes in altering the balance of incoming (solar) and outgoing (infrared and reflected shortwave) energy in the Earth-atmosphere system, and thus shows the relative importance of different factors in terms of their contribution to climate change. Positive forcing means the factor causes a warming effect and negative forcing means the factor causes a cooling effect.

Radiative forcing values presented here for GHGs and other factors come from the IPCC Fourth Assessment Report of Working Group I (2007). These radiative forcing values are the result of *global* changes in atmospheric concentrations of GHGs (see Section 2(c) above) and other factors, and are therefore not the result of U.S. transportation emissions in isolation. All values are for the year 2005 relative to pre-industrial times in 1750, represent global averages, and are expressed in watts per square meter 10 (W/m²).

 IPCC (2007d) concluded that the understanding of anthropogenic warming and cooling influences on climate has improved since the TAR, leading to *very high confidence*¹¹ that the global average net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 (+0.6 to +2.4) W/m².

Greenhouse gases have a positive forcing because they absorb and reradiate in all directions outgoing, infrared radiation that would otherwise directly escape into space. The combined radiative forcing due to the cumulative (i.e., 1750 to 2005) increase in atmospheric concentrations of CO_2 , CH_4 , and N_2O is +2.30 W/m² (with an uncertainty range of +2.07 to +2.53 W/m²) (see Figure 4.1). This positive radiative forcing, like the observed accumulation of these gases in the atmosphere, is primarily anthropogenic in origin. Furthermore, the IPCC (2007d) stated that the rate of increase in positive radiative forcing due to these three GHGs during the industrial era is "very likely to have been unprecedented in more than 10,000 years."

The positive radiative forcing due to CO_2 is the largest (+1.66 \pm 0.17 W/m²) (Figure 4.1), and has increased by 20% from 1995 to 2005, the largest change for any decade in at least the last 200 years. Methane is the second largest source of positive radiative forcing (+0.48 \pm 0.05 W/m²). Nitrous oxide has a positive radiative forcing of +0.16 (\pm 0.02) W/m².

The other three GHGs reported by the U.S. Inventory—HFCs, PFCs and SF₆—have a total radiative forcing in 2005 of ± 0.017 (± 0.002) W/m² (Forster et al., 2007).

¹⁰ Watts per square meter is the SI unit for radiative and other energy fluxes.

¹¹ According to IPCC terminology, "very high confidence" conveys a 9 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

Source: IPCC (2007d). Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and other important factors, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness.

The ozone-depleting substances covered under the Montreal Protocol (chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and chlorocarbons) are also strong GHGs and, as a group, contributed $+0.32~(\pm0.03)~\text{W/m}^2$ to anthropogenic radiative forcing in 2005. Their radiative forcing peaked in 2003 and is now beginning to decline (Forster et al., 2007). The radiative forcing due to the destruction of stratospheric ozone by these gases is estimated to be $-0.05~\pm~0.10~\text{W/m}^2$ with a medium level of scientific understanding (Solomon et al., 2007^{12}).

In addition to the six main GHGs directly emitted by human activities, and the gases covered by the Montreal Protocol, there are additional anthropogenic and natural factors that contribute to both positive and negative forcing. Tropospheric ozone changes due to emissions of ozone-forming chemicals, or precursors, (nitrogen oxides, carbon monoxide, and hydrocarbons) contribute significantly to positive forcing, +0.35 (+0.25 to +0.65) W/m². Unlike the GHGs mentioned above, tropospheric ozone is not as well mixed in the global atmosphere because its atmospheric lifetime is on the order of weeks to months

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¹² Solomon et al., 2007 citation refers to the Technical Summary in IPCC's 2007 Fourth Assessment Report, Working Group I.

(versus decades to centuries for the well-mixed GHGs). Tropospheric ozone is also a criteria air pollutant under the U.S. Clean Air Act.

Anthropogenic emissions of aerosols contribute to both positive and negative radiative forcing. Aerosols are non-gaseous substances that are suspended in the atmosphere, and are either solid particles or liquid droplets. Most aerosols, such as sulfates (which are mainly the result of SO_2 emissions), exert a negative forcing or cooling effect, as they reflect and scatter incoming solar radiation. Some aerosols, such as black carbon, cause a positive forcing by absorbing incoming solar radiation. IPCC (2007d) estimated that the net effect of all aerosols (primarily sulfate, organic carbon, black carbon, nitrate and dust) produce a cooling effect, with a total direct radiative forcing of -0.5 (-0.9 to -0.1) W/m² and an additional indirect cloud albedo (i.e., enhanced reflectivity)¹³ forcing of -0.7 (-1.8 to -0.3) W/m². These forcings are now better understood than at the time of the IPCC Third Assessment Report (2001), but nevertheless remain the dominant uncertainty in radiative forcing (IPCC, 2007d). Black carbon aerosols cause yet another forcing effect by decreasing the surface albedo of snow and ice (+0.1 (0.0 to +0.2) W/m²).

The radiative forcing from increases in stratospheric water vapor due to oxidation of CH_4 is estimated to be $+0.07 \pm 0.05~W/m^2$ (Solomon et al., 2007). The level of scientific understanding is low because the contribution of CH_4 to the corresponding vertical structure of the water vapor change near the tropopause is uncertain.

Changes in surface albedo due to human-induced land cover changes exert a forcing of -0.2 (-0.4 to 0.0) W/m². Changes in solar irradiance since 1750 are estimated to cause a radiative forcing of +0.12 (+0.06 to +0.30) W/m².

Although water vapor is the most abundant naturally occurring greenhouse gas, direct emissions of water vapor due to human activities make a negligible contribution to radiative forcing (hence its absence in Figure 3.1). However, as temperatures increase, tropospheric water vapor concentrations increase representing a key feedback but not a forcing of climate change (Solomon et al., 2007). Feedbacks are defined as processes in the climate system (such as a change in water vapor concentrations) that can either amplify or dampen the system's initial response to radiative forcing changes (NRC, 2003).

4(b) Global Changes in Temperature

Multiple lines of evidence lead to the robust conclusion that the climate system is warming. The IPCC (2007d) stated in its Fourth Assessment Report:

"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."

Air temperature is a main property of climate and the most easily measured, directly observable, and geographically consistent indicator of climate change. The extent to which observed changes in global

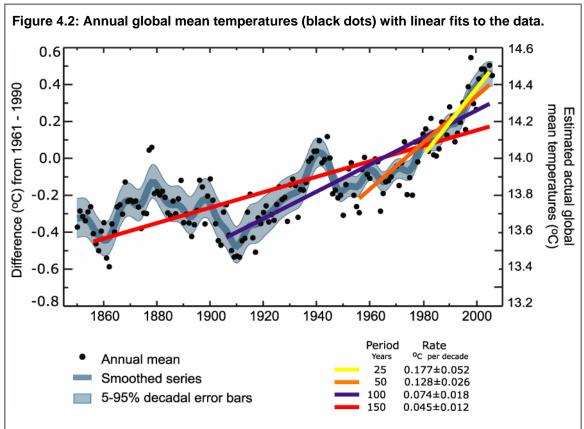
¹³ In addition to directly reflecting solar radiation, aerosols cause an additional, indirect negative forcing effect by enhancing cloud albedo (a measure of reflectivity or brightness). This occurs because aerosols act as particles around which cloud droplets can form; an increase in the number of aerosol particles leads to a greater number of smaller cloud droplets, which leads to enhanced cloud albedo. Aerosols also influence cloud lifetime and precipitation but no central estimates of these indirect forcing effects are estimated by IPCC.

 and continental temperature, and other climate factors, can be attributed to anthropogenic emissions of GHGs is addressed in Section 5 below.

Global Surface Temperatures

Surface temperature is calculated by processing data from thousands of world-wide observation sites on land and sea. Parts of the globe have no data, although data coverage has improved with time. The long-term mean temperatures are calculated by interpolating within areas with no measurements using the collected data available. Biases may exist in surface temperatures due to changes in station exposure and instrumentation over land, or changes in measurement techniques by ships and buoys in the ocean. It is likely that these biases are largely random and therefore cancel out over large regions such as the globe or tropics (Karl et al., 2006^{14}). Likewise, urban heat island effects are real but local, and have not biased the large-scale trends (Trenberth et al., 2007^{15}).

The following trends in global surface temperatures have been observed, according to the IPCC



Source: Solomon et al., (2007). The left hand axis shows temperature anomalies relative to the 1961 to 1990 average and the right hand axis shows estimated actual temperatures, both in $^{\circ}$ C. Linear trends are shown for the last 25 (yellow), 50 (orange), 100 (magenta) and 150 years (red). The smooth blue curve shows decadal variations with the decadal 90% error range shown as a pale blue band about that line. The total temperature increase from the period 1850 to 1899 to the period 2001 to 2005 is 0.76 $^{\circ}$ C \pm 0.19 $^{\circ}$ C (1.37 $^{\circ}$ F \pm 0.34 $^{\circ}$ F).

Fourth Assessment Report, Working Group I.

Karl et al. refers to the 2006 synthesis and assessment report "Temperature Trends in the Lower Atmosphere:
 Steps for Understanding and Reconciling Differences" from the U.S. Climate Change Science Program.
 Trenberth et al., 2007 citation refers to Chapter 3, "Surface and Atmospheric Climate Change" in IPCC's 2007

(Trenberth et al., 2007):

• Global mean surface temperatures have risen by $0.74^{\circ}\text{C} \pm 0.18^{\circ}\text{C}$ when estimated by a linear trend over the last 100 years (1906–2005) as shown by the magenta line in Figure 4.2. The rate of warming over the last 50 years is almost double that over the last 100 years ($0.13^{\circ}\text{C} \pm 0.03^{\circ}\text{C}$ vs. $0.07^{\circ}\text{C} \pm 0.02^{\circ}\text{C}$ per decade). The warmest years in the instrumental record of global surface temperatures are 1998 and 2005, with 1998 ranking first in one estimate, but with 2005 slightly higher in the other two estimates. 2002 to 2004 are the 3rd, 4th and 5th warmest years in the series since 1850. Eleven of the last 12 years (1995 to 2006) – the exception being 1996 – rank among the 12 warmest years on record since 1850. Temperatures in 2006 were similar to the average of the past 5 years.

• Land regions have warmed at a faster rate than the oceans. Warming has occurred in both land and oceans and in both sea surface temperature (SST) and nighttime marine air temperature over the oceans. However, for the globe as a whole, surface air temperatures over land have risen at about double the ocean rate after 1979 (more than 0.27°C per decade vs. 0.13°C per decade), with the greatest warming during winter (December to February) and spring (March to May) in the Northern Hemisphere. Recent warming is strongly evident at all latitudes in SSTs over each of the oceans.

• Average Arctic temperatures increased at almost twice the global average rate in the past 100 years. Arctic temperatures have high decadal variability, and a warm period was also observed from 1925 to 1945.

• Between 1901 and 2005, warming is statistically significant over most of the world's surface with the exception of an area south of Greenland and three smaller regions over the southeastern U.S. and parts of Bolivia and the Congo basin. The lack of significant warming at about 20% of the locations (Karoly and Wu, 2005), and the enhanced warming in other places, is likely to be a result of changes in atmospheric circulation. Warming is strongest over the continental interiors of Asia and northwestern North America and over some mid-latitude ocean regions of the Southern Hemisphere as well as southeastern Brazil.

• Since 1979, warming has been strongest over western North America, northern Europe and China in winter, Europe and northern and eastern Asia in spring, Europe and North Africa in summer and northern North America, Greenland and eastern Asia in autumn. Temperatures over mainland Antarctica (south of 65°S) have not warmed in recent decades, but it is virtually certain that there has been strong warming over the last 50 years in the Antarctic Peninsula region (Thompson and Solomon, 2002; Turner et al., 2005).

The pattern of temperature change over Antarctica has been simulated in models in response to stratospheric ozone depletion and combined stratospheric ozone depletion and GHG increases (Baldwin et al., 2007¹⁶). See section 6(g) for more information.

Global Upper Air Temperatures

Temperature measurements have also been made above the Earth's surface over the past 50 to 60 years using radiosondes (balloon-borne instruments) and for the past 28 years using satellites. These measurements support the analysis of trends and variability in the troposphere (surface to 10-16 km) and stratosphere (10-50 km above the earth's surface).

¹⁶ Baldwin et al., 2007 citation refers to Chapter 5, "Climate-Ozone Connections" in WMO's Scientific Assessment of Ozone Depletion, 2006.

The U.S. Climate Change Science Program prepared a report which assessed temperature changes in the atmosphere, differences in these changes at various levels in the atmosphere, and our understanding of the causes of these changes and differences. It concluded (Karl et al., 2006): "...the most recent versions of all available data sets show that both the surface and troposphere have warmed, while the stratosphere has cooled. These changes are in accord with our understanding of the effects of radiative forcing agents and with the results from model simulations."

The IPCC (Trenberth et al., 2007) re-affirmed the major conclusions of this CCSP report finding:

• New analyses of radiosondes and satellite measurements of lower- and mid-tropospheric temperature show warming rates that are similar to those of the surface temperature record and are consistent within their respective uncertainties.

• The satellite tropospheric temperature record is broadly consistent with surface temperature trends. The range (due to different data sets) of global surface warming since 1979 is 0.16°C to 0.18°C per decade compared to 0.12°C to 0.19°C per decade for estimates of tropospheric temperatures measured by satellite.

• Lower-tropospheric temperatures measured by radiosondes have slightly greater warming rates than those at the surface over the period 1958 to 2005. The radiosonde record is markedly less spatially complete than the surface record and increasing evidence suggests that it is very likely that a number of records have a cooling bias, especially in the tropics.

Lower stratospheric temperatures have cooled since 1979. Estimates from adjusted radiosondes, satellites and re-analyses are in qualitative agreement, suggesting a lower-stratospheric cooling of between 0.3°C and 0.6°C per decade since 1979.

Global Surface Temperatures Over the Last 2,000 Years

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Instrumental surface temperature records only began in the late century, when sufficiently large global network of measurements was in place to reliably global compute mean temperatures. To estimate temperatures further back in time, scientists analyze proxy evidence from sources such as tree rings, corals, ocean and lake sediments, cave deposits, boreholes, cores, glaciers, and documentary evidence. Α longer temperature record can help place the 20th century warming into a historical context.

The National Research Council conducted a study

global average) surface temperature variations from six research teams 0.6 0.6 0.4 0.4 ပ 0.2 0.2 Temperature anomaly (deg 0.0 0.0 -0.2 -0.2 -0.4 -0.4 -0.6 -0.6 -0.8 -0.8 -1.0 -1.0 -12 -12 1100 1300 1500 1700 900 1900 Year

Figure 4.3: Reconstructions of (Northern Hemisphere average or

Source: NRC (2006b) Reconstructions of (Northern Hemisphere average or global average) surface temperature variations from six research teams (in different color shades) along with the instrumental record of global average surface temperature (in black). Each curve illustrates a somewhat different history of temperature changes, with a range of uncertainties that tend to increase backward in time (as indicated by the shading).

Borehole temperatures (Huang et al. 2000) — Glacier lengths (Oerlemans 2005)

—Multiproxy (Moberg et al. 2005)

Tree rings (Esper et al. 2002)

to describe and assess the state of scientific efforts to reconstruct surface temperature records for the Earth over approximately the last 2,000 years and the implications of these efforts for our understanding of global climate change. It found (NRC, 2006b):

Multiproxy (Mann and Jones 2003)

-Instrumental record (Jones et al. 2001)

Multiproxy (Hegerl et al. 2006)

- Large-scale surface temperature reconstructions, as illustrated in Figure 4.3, yield a generally consistent picture of temperature trends during the preceding millennium, including relatively warm conditions centered around A.D. 1000 (identified by some as the "Medieval Warm Period") and a relatively cold period (or "Little Ice Age") centered around 1700.
- It can be said with a high level of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries. The observed warming in the instrumental record shown in Figure 4.2 supports this conclusion.
- Less confidence can be placed in large-scale surface temperature reconstructions for the period from A.D. 900 to 1600. Presently available proxy evidence indicates that temperatures at many, but not all, individual locations were higher during the past 25 years than during any period of comparable length since A.D. 900. The uncertainties associated with reconstructing hemispheric mean or global mean temperatures from these data increase substantially backward in time through this period and are not yet fully quantified.

 Very little confidence can be assigned to statements concerning the hemispheric mean or global mean surface temperature prior to about A.D. 900 because of sparse data coverage and because the uncertainties associated with proxy data and the methods used to analyze and combine them are larger than during more recent time periods.

Considering this study and additional research, the IPCC (2007d) concluded: "Paleoclimatic information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years."

4(c) U.S. changes in temperatures

Like global mean temperatures, U.S. temperatures also warmed during the 20th and into the 21st century. According to the National Oceanic and Atmospheric Administration (NOAA, 2007):¹⁷

• U.S. average annual temperatures are now approximately 1.0°F warmer than at the start of the 20th century, with an increased rate of warming over the past 30 years.

• The 2006 average annual temperature for the contiguous U.S. was the 2nd warmest on record and within 0.1°F of the record set in 1998.

• The past nine years have all been among the 25 warmest years on record for the contiguous U.S., a streak which is unprecedented in the historical record.

The last eight 5-year periods (2002-2006, 2001-2005, 2000-2004, 1999-2003, 1998-2002, 1997-2001, 1996-2000, 1995-1999), were the warmest 5-year periods (i.e. pentads) in the last 112 years of national records, illustrating the anomalous warmth of the last decade.

¹⁷ U.S. temperature data analyzed by National Aeronautics and Space Administration (NASA) show similar trends over the past 100 years although, due to differences in datasets, processing and analysis, it finds 1934 was the warmest on record for the contiguous U.S., followed by 1998 and 1921. 2006 was the fourth warmest year on record in its analysis. For more information on NASA's temperature data, see: http://data.giss.nasa.gov/gistemp/

Data analyzed from NOAA's National Climatic Data Center U.S. Historical Climate Network¹⁸ (USHCN), as illustrated in Figure 4.4, indicate warming has occurred throughout most of the U.S., with all but three of the eleven climate regions showing an increase of more than 1°F since 1901 through 2005 (NOAA, 2007). The greatest temperature increase occurred in Alaska (3.3°F per century). The Southeast experienced a very slight cooling trend over the entire period (-0.04°F per century), but shows warming since 1979.

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Including all of North America in its assessment of regional temperatures, the IPCC (Field et al., 2007¹⁹) stated:

- For the period 1955-2005, the greatest warming occurred in Alaska and north-western Canada, with substantial warming in the continental interior and modest warming in the south-eastern U.S. and eastern Canada.
- Spring and winter show the greatest changes in temperature

temperatures.

Figure 4.4: Map of the United States, depicting regional U.S. temperature trends for the period 1901 to 2005.

West North Central Central North Central North Central Southeast

Alaska Hawaii

Temperature change (°F per century):

greatest changes in temperature and daily minimum (night-time) temperatures have warmed more than daily maximum (daytime)

Red shades indicate warming over the period and blue shades

4(d) Global changes in precipitation

A consequence of rising temperature is increased evaporation, provided that adequate surface moisture is available (e.g., over the oceans and other moist surfaces). The average atmospheric water vapor content has increased since at least the 1980s over land and ocean as well as in the upper troposphere (IPCC, 2007d). When evaporation increases, more water vapor is available for precipitation producing weather systems leading to precipitation increases in some areas. Conversely, enhanced evaporation and evapotranspiration from warming accelerates land surface drying and increases the potential incidence and severity of droughts in other areas.

indicate cooling over the period.

Observations show that changes are occurring in the amount, intensity, frequency and type of precipitation. According to the IPCC (Trenberth et al., 2007):

¹⁸ Data obtained from: http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html

¹⁹ Field et al., 2007 citation refers to Chapter 14, "North America" in IPCC's 2007 Fourth Assessment Report, Working Group II.

- Long-term trends from 1900 to 2005 have been observed in precipitation amount over many large regions. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Precipitation is highly variable spatially and temporally, and data are limited in some regions.

• More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought. The regions where droughts have occurred seem to be determined largely by changes in sea surface temperatures (SSTs), especially in the tropics, through associated changes in the atmospheric circulation and precipitation. Decreased snowpack and snow cover have also been linked to droughts.

• It is likely that there have been increases in the number of heavy precipitation events (e.g., 95th percentile) within many land regions, even in those where there has been a reduction in total precipitation amount, consistent with a warming climate and observed significant increasing amounts of water vapor in the atmosphere.

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resulted in rain rather than snow in locations and seasons where climatological average (1961–1990) temperatures were close to 0°C. **U.S.** changes in precipitation

Rising temperatures have generally

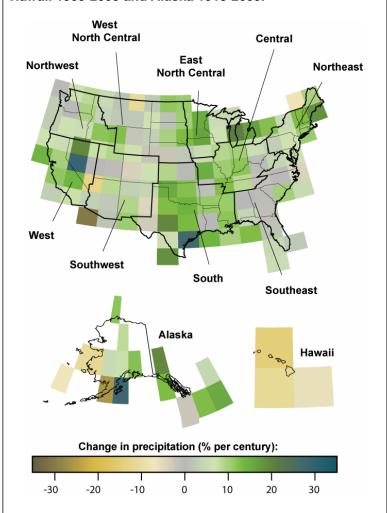
4(e)

Data analyzed from NOAA's National Climatic Data Center U.S. Historical Climate Network (USHCN)²⁰ show that over the contiguous U.S., total annual precipitation increased at an average rate of 6% per century from 1901-2005. The greatest increases in precipitation were in the East North Central climate region (12% per century) and the South (11%). Precipitation in the Northeast increased by 7%, in the Southeast by 3%, the Central U.S. by 8%, the West North Central by 3%, the Southwest by 1%, the West by 9%, and the Northwest by 5%.

Outside the contiguous U.S., Alaska experienced a precipitation increase of about 6% per century (since records began in 1918) and Hawaii experienced a decrease of just over 9% per century (since records begin in 1905).

Despite the overall national trend towards wetter conditions, a severe drought has affected the southwest U.S. from 1999 through 2007 (see Section 4(k) which is indicative of significant variability in regional precipitation patterns over time and space.

Figure 4.5: Map of the United States, depicting precipitation trends for the contiguous U.S. 1901-2005, Hawaii 1905-2005 and Alaska 1918-2005.



Green shades indicate a trend towards wetter conditions over the period, and brown shades indicate a trend towards dryer conditions. No data are available for areas shaded in white.

4(f) Global sea level rise

There is strong evidence that global sea level gradually rose in the 20th century and is currently rising at an increased rate, after a period of little change between AD 0 and AD 1900 (IPCC, 2007a).

According to Bindoff et al. (2007²¹), there is high confidence that the rate of sea level rise increased between the mid-19th and mid-20th centuries (Bindoff et al., 2007²²). The average rate of sea level rise

²⁰ Data obtained from: http://www.ncdc.noaa.gov/oa/climate/research/ushcn/ushcn.html

²¹ Bindoff et al., 2007 citation refers to Chapter 5, "Observations: Oceanic Climate Change and Sea Level" in IPCC's 2007 Fourth Assessment Report, Working Group I.

²² Bindoff et al., 2007 refers to Chapter 5, "Observations: Oceanic Climate Change and Sea Level" in IPCC's 2007 Fourth Assessment Report, Working Group I.

measured by tide gauges from 1961 to 2003 was 1.8 ± 0.5 mm per year (Bindoff et al., 2007). The global average rate of sea level rise measured by satellite altimetry during 1993 to 2003 was 3.1 ± 0.7 mm per year (Bindoff et al., 2007). Coastal tide gauge measurements confirm this observation. It is unclear whether the faster rate for 1993 to 2003 is a reflection of short-term variability or an increase in the longer-term trend (Bindoff et al., 2007). The total 20^{th} century sea level rise is estimated to be 0.17 ± 0.05 m (Bindoff et al., 2007).

Two major processes lead to changes in global mean sea level on decadal and longer time scales: i) thermal expansion, and ii) the exchange of water between oceans and other reservoirs (glaciers and ice caps, ice sheets, and other land water reservoirs). It is believed that on average, over the period from 1961 to 2003, thermal expansion contributed about one-quarter of the observed sea level rise, while melting of land ice accounted for less than half; the full magnitude of the observed sea level rise was not satisfactorily explained by the available data sets (Bindoff et al., 2007). During this period, global ocean temperature rose by 0.10° C from the surface to a depth of 700 m, contributing an average of 0.4 ± 0.1 mm per year to sea level rise (Bindoff et al., 2007). The contribution from ice was approximately 0.7 ± 0.5 mm per year (Lemke et al., 2007^{23}).

For recent years (1993-2003) for which the observing system is much better, thermal expansion and melting of land ice each account for about half of the observed sea level rise, although there is some uncertainty in the estimates. Thermal expansion contributed about 1.6 ± 0.5 mm per year, reflecting a high rate of warming for the period relative to 1961 to 2003 (Bindoff et al., 2007). The total contribution from melting ice to sea level change between 1993 and 2003 ranged from 1.2 ± 0.4 mm per year. The rate increased over the 1993 to 2003 period primarily due to increasing losses from mountain glaciers and ice caps, from increasing surface melt on the Greenland Ice Sheet and from faster flow of parts of the Greenland and Antarctic Ice Sheets (Lemke et al., 2007).

Thermal expansion and exchanges of water between oceans and other reservoirs cause changes in the global mean as well as geographically non-uniform sea level change. Other factors influence changes at the regional scale, including changes in ocean circulation or atmospheric pressure, and geologic processes (Bindoff et al., 2007). Satellite measurements (for the period 1993-2003) provide unambiguous evidence of regional variability of sea level change (Bindoff et al., 2007). In some regions, rates of rise have been as much as several times the global mean, while sea level is falling in other regions. According to IPCC (Bindoff et al., 2007), the largest sea level rise since 1992 has taken place in the western Pacific and eastern Indian Oceans, while nearly all of the Atlantic Ocean shows sea level rise during the past decade with the rate of rise reaching a maximum (over 2 mm yr⁻¹) in a band running east-northeast from the U.S. east coast. Sea level in the eastern Pacific and western Indian Oceans has been falling.

4(g) U.S. sea level rise

Sea level²⁴ has been rising 0.08-0.12 inches per year (2.0-3.0 mm per year) along most of the U.S. Atlantic and Gulf coasts. The rate of sea level rise varies from about 0.36 inches per year (10 mm per year) along the Louisiana Coast (due to land sinking), to a drop of a few inches per decade in parts of Alaska (because land is rising). Records from the coast of California indicate that sea levels have risen almost 18 cm during the past century (California Energy Commission, 2006).

Rosenzweig et al. (2007) document studies that find 75% of the shoreline removed from the influence of spits, tidal inlets and engineering structures is eroding along the U.S. East Coast probably due to sea level

²³ Lemke et al., 2007 refers to Chapter 4, "Observations: Changes in Snow, Ice and Frozen Ground" in IPCC's 2007 Fourth Assessment Report, Working Group I.

²⁴ U.S. sea level data obtained from the Permanent Service for Mean Sea Level < http://www.pol.ac.uk/psmsl/> of the Proudman Oceanographic Laboratory.

rise. They also cite studies reporting losses in coastal wetlands observed in Louisiana, the mid-Atlantic region, and in parts of New England and New York, in spite of recent protective environmental regulations.

4(h) Global changes in physical and biological systems

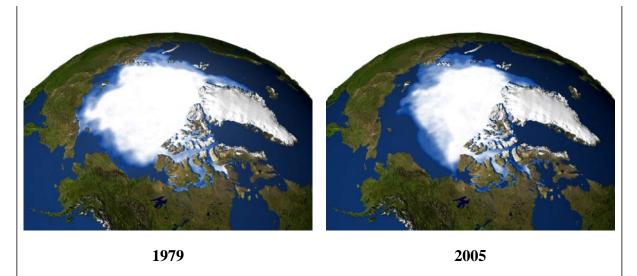
Physical and biological systems on all continents and in most oceans are already being affected by recent climate changes, particularly regional temperature increases (very high confidence) (Rosenzweig. et al., 2007²⁵). Climatic effects on human systems, although more difficult to discern due to adaptation and non-climatic drivers, are emerging (medium confidence) (Rosenzweig. et al., 2007). The majority of evidence comes from mid- and high latitudes in the Northern Hemisphere, while documentation of observed changes in tropical regions and the Southern Hemisphere is sparse (Rosenzweig. et al., 2007). Hence, the findings presented in this section apply generally to the globe but most directly to Europe and North America (including the U.S.) where these observational studies were conducted. The extent to which observed changes discussed here can be attributed to anthropogenic GHG emissions is discussed in

1718 Cryosphere (Snow and Ice)

Section 5.

Observations of the cryosphere (the "frozen" component of the climate system) have revealed changes in sea ice, glaciers and snow cover, freezing and thawing, and permafrost. According to IPCC, the following physical changes have been observed:

• Satellite data since 1978 show that annual average Arctic sea ice extent has shrunk by 2.7 ± 0.6 % per decade, with larger decreases in summer of 7.4 ± 2.4 % per decade. The extent of the sea ice loss



These two images, constructed from satellite data, compare arctic sea ice concentrations in September of 1979 and 2005 (ACIA, 2005, images courtesy of NASA).

Figure 4.6 Arctic Sea Ice Concentrations Comparisons

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²⁵ Rosenzweig et al., 2007 refers to Chapter 1 "Assessment of observed changes and responses in natural and managed systems" in IPCC's 2007 Fourth Assessment Report, Working Group 2.

between 1979 and 2005 can be seen in Figure 4.6. Antarctic sea ice extent, however, shows no statistically significant average trends (IPCC, 2007d).

The average sea ice thickness in the central Arctic has very likely decreased by up to 1 m from 1987 to 1997, based upon submarine-derived data. Model-based reconstructions support this, suggesting an arctic-wide reduction of 0.6 to 0.9 m over the same period (Lemke et al., 2007).

• Mountain glaciers and snow cover have declined on average in both hemispheres. Northern hemisphere snow cover observed by satellite over the 1966 to 2005 period decreased in every month except November and December, with a stepwise drop of 5% in the annual mean in the late 1980s. In the Southern Hemisphere, the few long records or proxies mostly show either decreases or no changes in the past 40 years or more. The strongest mass losses of mountain glaciers (per unit area) have been observed in Patagonia, Alaska and the northwestern U.S. and southwest Canada. Because of the corresponding large areas, the biggest contributions to sea level rise came from Alaska, the Arctic and the Asian high mountains (Lemke et al., 2007).

• Freeze-up date for river and lake ice has occurred later at a rate of 5.8 ± 1.6 days per century, averaged over available data for the Northern Hemisphere spanning the past 150 years. Breakup date has occurred earlier at a rate of 6.5 ± 1.2 days per century (Lemke et al., 2007).

• Temperatures at the top of the permafrost layer have generally increased since the 1980s in the Arctic (by up to 3°C). The permafrost base has been thawing at a rate ranging up to 0.04 m per year in Alaska since 1992 and 0.02 m per year on the Tibetan Plateau since the 1960s. The maximum area covered by seasonally frozen ground has decreased by 7% in the Northern Hemisphere since 1900, with a decrease in spring of up to 15% (Lemke et al., 2007).

There are additional effects related to changes in the cryosphere. Melting of highly reflective snow and ice reveals darker land and ocean surfaces, increasing absorption of the sun's heat and further warming the planet. Increases in glacial melt and river runoff add more freshwater to the ocean, raising global sea level.

Hydrosphere

The term "hydrosphere" refers to the component of the climate system comprising liquid surface and subterranean water, such as rivers, lakes, and underground water. Several changes in these features have been observed, as summarized by the IPCC (Rosenzweig et al., 2007):

• Documented trends in severe droughts and heavy rains show that hydrological conditions are becoming more intense in some regions. Globally, very dry areas (Palmer Drought Severity Index—PDSI—less than or equal to -3.0) have more than doubled since the 1970s due to a combination of El Niño-Southern Oscillation events and surface warming. Very wet areas (PDSI greater than or equal to +3.0) declined by about 5% since the 1970s, with precipitation as the major contributing factor during the early 1980s and temperature more important thereafter. The areas of increasing wetness include the Northern Hemisphere high latitudes and equatorial regions.

• Climate change signals related to increasing runoff and stream flow have been observed over the last century in many regions, particularly in basins fed by glaciers, permafrost, and snowmelt. Evidence includes increases in average runoff of Arctic rivers in Eurasia, which has been at least partly correlated with climate warming, and earlier spring snowmelt and increase in winter base flow in North America and Eurasia due to enhanced seasonal snow melt associated with climate warming.

disappearance in permafrost have been reported in the Arctic.

et al., 2007).

Biosphere

4(i) U.S. changes in physical and biological systems

Many of the global changes in physical and biological systems mentioned in 4(h) broadly apply to the U.S. Some U.S.-specific changes in these systems cited in IPCC's Fourth Assessment Report are described in this subsection, as well as in section 11(a) for physical systems related to water resources and section 14(a) related to biological systems. Of all the observed changes to physical systems assessed by IPCC (Rosenzweig et al., 2007) for North America (totaling 355), 94% of them were consistent with

According to IPCC, terrestrial ecosystems and marine and freshwater systems show that recent warming is strongly affecting natural biological systems (very high confidence) (Rosenzweig et al., 2007):

Freshwater lakes and rivers are experiencing increased water temperatures and changes in water chemistry. Surface and deep lake-waters are warming, with advances and lengthening of periods of thermal stability in some cases associated with physical and chemical changes such as increases in

salinity and suspended solids, and a decrease in nutrient content. Lake formation and subsequent

Changes in river discharge as well as in droughts and heavy rains in some regions indicate that

hydrological conditions have become more intense but significant trends in floods and in evaporation and

evapotranspiration have not been detected globally. Some local trends in reduced groundwater and lake

levels have been reported, but studies have been unable to separate the effects of variations in temperature

and precipitation from the effects of human interventions such as groundwater management (Rosenzweig

- The overwhelming majority of studies of regional climate effects on terrestrial species reveal consistent responses to warming trends, including poleward and elevational range shifts of flora and fauna. Changes in abundance of certain species, including limited evidence of a few local disappearances, and changes in community composition over the last few decades have been attributed to climate change.
- Responses of terrestrial species to warming across the northern hemisphere are well documented by changes in the timing of growth stages, especially the earlier onset of spring events, migration, and lengthening of the growing season. Changes in phenology (the timing of annual phenomena of animal and plant life) include clear temperature-driven extension of the growing season by up to 2 weeks in the second half of the 20th century in mid- and high northern latitudes, mainly due to an earlier spring, but partly due also to a later autumn. Egg-laying dates have advanced in many bird species, and many small mammals have been found to come out of hibernation and to breed earlier in the spring now than they did a few decades ago.
- Many observed changes in phenology and distribution of marine species have been associated with rising water temperatures, as well as other climate-driven changes in salinity, oxygen levels, and circulation. For example, plankton has moved poleward by 10° latitude over a period of 4 decades in the North Atlantic. While there is increasing evidence for climate change impacts on coral reefs, discerning the impacts of climate-related stresses from other stresses (*e.g.* over fishing and pollution) is difficult. Warming of lakes and rivers is affecting abundance and productivity, community composition, phenology, distribution and migration of freshwater species (high confidence).

changes one would expect with average warming. Similar consistency was found between observed biological system changes and warming for North America (see discussion below under *biosphere*).

Cryosphere (Snow and Ice)

In North America, from 1915 to 2004, snow covered area increased in November, December and January due to increases in precipitation. However, snow cover decreased during the latter half of the 20th century, especially during the spring over western North America (Groisman et al., 2004 in Lemke et al., 2007). Shifts towards earlier melt by about eight days since the mid-1960s were also observed in northern Alaska (Stone et al., 2002 in Lemke et al., 2007).

The IPCC (Lemke et al., 2007) cites a study (Dyurgerov and Meier, 2005) documenting glacier mass balance loss in the northwest U.S. and Alaska, with losses especially rapid in Alaska after the mid-1990s. Rosenzweig et al. (2007) document evidence of present crustal uplift in response to recent glacier melting in Alaska (Larsen et al., 2005).

Hydrosphere

Rosenzweig et al. (2007) indicate surface water temperatures have warmed by 0.2 to 2°C in lakes and rivers in North America since the 1960s. They also discuss evidence for an earlier occurrence of spring peak river flows and an increase in winter base flow in basins with important seasonal snow cover in North America.

Biosphere

The IPCC (Rosenzweig et al., 2007) assessed a multitude of studies that find changes in terrestrial ecosystems and marine and freshwater systems in North America. Of 455 biological observations assessed from these studies, 92% were consistent with the changes expected due to average warming.

4(j) Global extreme events

Climate is defined not simply as average temperature and precipitation but also by the type, frequency and intensity of extreme events. The IPCC documents observed changes in climate extremes related to temperature, precipitation, tropical cyclones, and sea level. The changes described apply generally to all parts of the globe, including the U.S., although there are some regional and local exceptions due to patterns of natural climate variability. Current observations are summarized here, projected trends are covered in Section 6, and the sectoral impacts of these changes are covered as relevant in Sections 7 to 15.

Temperature

Widespread changes in extreme temperatures have been observed in the last 50 years. Cold days, cold nights, and frost have become less frequent, while hot days, hot nights, and heat waves have become more frequent (IPCC, 2007d). A widespread reduction in the number of frost days in mid-latitude regions, an increase in the number of warm extremes and a reduction in the number of daily cold extremes are observed in 70 to 75% of the land regions where data are available. The most marked changes are for cold (lowest 10%, based on 1961–1990) nights, which have become rarer over the 1951 to 2003 period. Warm (highest 10%) nights have become more frequent.

Precipitation and Storms

It is likely that there have been increases in the number of heavy precipitation events²⁶ within many land regions, even in those where there has been a reduction in total precipitation amount, consistent with a warming climate and observed significant increasing amounts of water vapor in the atmosphere. Increases have also been reported for rarer precipitation events (1 in 50 year return period), but only a few regions have sufficient data to assess such trends reliably (Trenberth et al., 2007).

More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics (IPCC, 2007d). Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought (IPCC, 2007d).

Globally, estimates of the potential destructiveness of hurricanes show a significant upward trend since the mid-1970s, with a trend towards longer lifetimes and greater storm intensity, and such trends are strongly correlated with tropical SST (Trenberth et al., 2007). There is no clear trend in the annual numbers of tropical cyclones (IPCC, 2007d).

High Sea Level

Apart from non-climatic events such as tsunamis, extreme sea levels occur mainly in the form of storm surges generated by tropical or extra tropical cyclones. There is evidence for an increase in extreme high sea level since 1975 based upon an analysis of 99th percentiles of hourly sea level at 141 stations over the globe (Bindoff et al., 2007).

4(k) U.S. extreme events

Many of the global changes in extreme events mentioned in 4(j) broadly apply to the U.S. Some U.S. specific changes in extremes cited in IPCC's AR4 are described in this subsection.

Temperature

The IPCC (Trenberth et al., 2007) cites North America regional studies that all show patterns of changes in temperature extremes consistent with a general warming. For example, Robeson (2004 in Trenberth et al., 2007) found intense warming of the lowest daily minimum temperatures over western and central North America. Trenberth et al. (2007) caution the observed changes of the tails of the temperature distributions are often more complicated than a simple shift of the entire distribution would suggest.

Precipitation and Storms

In the contiguous U.S., Kunkel et al. (2003; in Trenberth et al., 2007) and Groisman et al. (2004; in Trenberth et al., 2007) found statistically significant increases in heavy precipitation (the heaviest 5%) and very heavy precipitation (the heaviest 1%) of 14 and 20%, respectively. Much of this increase occurred during the last three decades of the 20th century and is most apparent over the eastern parts of the country. There is also evidence from Europe and the U.S. that the relative increase in precipitation extremes is larger than the increase in mean precipitation (Trenberth et al., 2007).

In the western U.S., diminishing snow pack and subsequent reductions in soil moisture appear to be factors in recent drought conditions (Trenberth et al., 2007). This drought has also been attributed to changes in atmospheric circulation associated with warming of the western tropical Pacific and Indian oceans as well as multidecadal fluctuations (Hoerling and Kumar, 2003; McCabe et al., 2004; in Trenberth et al., 2007).

²⁶ Heavy precipitation events refer to those in the 95th percentile of precipitation events.

There is observational evidence for an increase in intense tropical cyclone activity in the North Atlantic (where cyclones develop that affect the U.S. East and Gulf Coasts) since about 1970, correlated with increases of tropical sea surface temperatures (IPCC, 2007d). Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity.

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High Sea Level

Studies of the longest records of extremes in sea level are restricted to a small number of locations. Consistent with global changes, U.S.-based studies document increases in extreme sea level closely following the rise in mean sea level (Bindoff et al., 2007).

Section 5

2 3

Attribution of Observed Climate Change to Anthropogenic Greenhouse Gas Emissions at the Global and Continental Scale

This section addresses the extent to which observed climate change at the global and continental or national scale (described in Section 4) can be attributed to *global* anthropogenic emissions of GHGs. Section 2 describes the share of the U.S. transportation sector to U.S. and global anthropogenic emissions of GHGs, and the resultant share of U.S. transportation emissions to global increases in atmospheric concentrations of GHGs.

Evidence of the effect of anthropogenic GHG emissions on the climate system, as well as climate-sensitive systems and sectors, has increased over the last 15 years or so and even since the last IPCC assessment published in 2001. The evidence in the recent IPCC Fourth Assessment Report (2007) is based on analyses of global- and continental-scale temperature increases, changes in other climate variables and physical and biological systems, and the radiative forcing caused by anthropogenic versus natural factors.

5(a) Attribution of observed climate change to anthropogenic emissions

Computer-based climate models are the primary tools used for simulating the likely patterns of response of the climate system to different forcing mechanisms (both natural and anthropogenic). Confidence in these models comes from their foundation in accepted physical principles and from their ability to reproduce observed features of current climate and past climate changes (IPCC, 2007a). For additional discussion on the strengths and limitations of models, see Section 6(b). Attribution studies evaluate whether observed changes are consistent with quantitative responses to different forcings (from greenhouse gases, aerosols and natural forcings such as changes solar intensity) represented in well-tested models, and are not consistent with alternative physically plausible explanations.

Studies to detect climate change and attribute its causes using patterns of observed temperature change show clear evidence of human influences on the climate system (Karl et al., 2006). Discernible human influences extend to additional aspects of climate including ocean warming, continental-average temperatures, temperature extremes and wind patterns (Hegerl et al., 2007²⁷).

Temperature

IPCC statements on the linkage between greenhouse gases and temperatures have strengthened since its early assessments (Solomon et al., 2007). The IPCC's First Assessment Report in 1990 contained little observational evidence of a detectable anthropogenic influence on climate (IPCC, 1990). In its Second Assessment Report in 1995, it stated the balance of evidence suggests a discernible human influence on the climate of the 20th century (IPCC, 1996). The Third Assessment Report in 2001 concluded that most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations (IPCC, 2001b). The conclusion in IPCC's 2007 Fourth Assessment Report (2007b) is the strongest yet:

²⁷ Hegerl et al., 2007 citation refers to Chapter 9, "Understanding and Attributing Climate Change" in IPCC's 2007 Fourth Assessment Report, Working Group I.

Most of the observed increase in global average temperatures since the mid-20th century is very likely²⁸ due to the observed increase in anthropogenic greenhouse gas concentrations.

The increased confidence in the greenhouse gas contribution to the observed warming results from (Hegerl. et al., 2007):

• an expanded and improved range of observations allowing attribution of warming to be more fully addressed jointly with other changes in the climate system

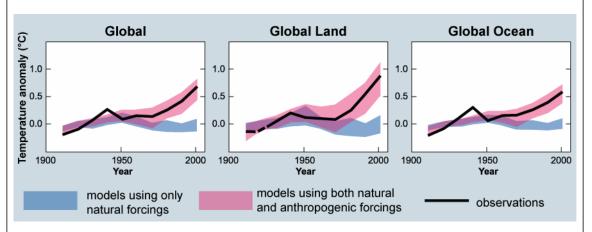
• improvements in the simulation of many aspects of present mean climate and its variability on seasonal to inter-decadal time scales

 more detailed representations of processes related to aerosol and other forcings in models
 simulations of 20th-century climate change that use many more models and much more complete anthropogenic and natural forcings

 multi-model ensembles that increase confidence in attribution results by providing an improved representation of model uncertainty

 Climate model simulations run by the IPCC, shown in Figure 5.1, suggest natural forcings alone cannot explain the observed warming (for the globe, the global land and global ocean). The observed warming can only be reproduced with models that contain both natural and anthropogenic forcings.

Figure 5.1: Comparison of observed global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings.



Source: IPCC (2007d). Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.

Additional evidence documented in the IPCC report supports its statement linking warming to increasing concentrations of greenhouse gases (Hegerl et al., 2007):

²⁸ According to IPCC terminology, "very likely" conveys a 90 to 99% probability of occurrence. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

- Warming of the climate system has been detected in changes of surface and atmospheric temperatures in the upper several hundred meters of the ocean, and in contributions to sea level rise. Attribution studies have established anthropogenic contributions to all of these changes.
- Analyses of paleoclimate data have increased confidence in the role of external influences on climate. Coupled climate models used to predict future climate have been used to reproduce key features of past climates using boundary conditions and radiative forcing for those periods.

The IPCC states that it is very unlikely that the global pattern of warming observed during the past half century is due to only known natural external causes (solar activity and volcanoes) since the warming occurred in both the atmosphere and ocean and took place when natural external forcing factors would likely have produced cooling (Hegerl et al., 2007). It also states greenhouse gas forcing alone would likely have resulted in warming greater than observed if there had not been an offsetting cooling effect from aerosols and natural forcings during the past half century (Hegerl et al., 2007).

Not only has anthropogenic signal been detected for the surface temperatures, but evidence has also accumulated of an anthropogenic influence through the vertical profile the atmosphere. Fingerprint studies²⁹ have identified greenhouse gas and sulfate aerosol signals observed surface temperature records. stratospheric ozone depletion signal in stratospheric temperatures, and the combined effects of these forcing agents in the vertical structure of atmospheric temperature changes (Karl et al., 2006). However, one important inconsistency may have been identified in the tropics. In the tropics, most observational data show more warming at the surface than in the troposphere, while almost all model simulations have larger warming aloft than

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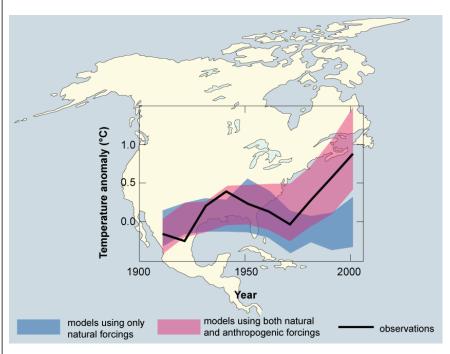
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Figure 5.2: Comparison of observed North American changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings.



Source: Hegerl et al. (2007). Decadal averages of observations are shown for the period 1906 to 2005 (black line) plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.

²⁹ Fingerprint studies use rigorous statistical methods to compare the patterns of observed temperature changes with model expectations and determine whether or not similarities could have occurred by chance. Linear trend comparisons are less powerful than fingerprint analyses for studying cause-effect relationships, but can highlight important differences and similarities between models and observations (as in Figures 5.1 and 5.2).

at the surface. A possible explanation for this inconsistency is error in the observations, but the issue is still under investigation (Karl et al., 2006).

The substantial anthropogenic contribution to surface temperature increases likely applies to every continent except Antarctica (which has insufficient observational coverage to make an assessment) since the middle of the 20th century (Hegerl. et al., 2007). Figure 5.2 indicates North America's observed temperatures over the last century can only be reproduced using model simulations containing both natural and anthropogenic forcings. Difficulties remain in attributing temperature changes on smaller than continental scales and over time scales of less than 50 years. Attribution at these scales, with limited exceptions, has not yet been established (Hegerl et al., 2007).

Temperature extremes have also likely been influenced by anthropogenic forcing. Many indicators of climate extremes, including the annual numbers of frost days, warm and cold days, and warm and cold nights, show changes that are consistent with warming (Hegerl et al., 2007). An anthropogenic influence has been detected in some of these indices, and there is evidence that anthropogenic forcing may have substantially increased the risk of extremely warm summer conditions regionally, such as the 2003 European heat wave (Hegerl et al., 2007).

Additional Climate Variables

There is evidence of anthropogenic influence in other parts of the climate system. The IPCC noted the following examples (Hegerl et al., 2007):

• Trends over recent decades in the Northern and Southern Annular Modes³⁰, which correspond to sea level pressure reductions over the poles, are likely related in part to human activity, affecting storm tracks, winds and temperature patterns in both hemispheres. Models reproduce the sign of the Northern Annular Mode trend, but the simulated response is smaller than observed. Models including both greenhouse gas and stratospheric ozone changes simulate a realistic trend in the Southern Annular Mode, leading to a detectable human influence on global sea level pressure patterns.

• The latitudinal pattern of change in land precipitation and observed increases in heavy precipitation over the 20th century appear to be consistent with the anticipated response to anthropogenic forcing.

• It is more likely than not that anthropogenic influence has contributed to increases in the frequency of the most intense tropical cyclones. Stronger attribution to anthropogenic factors is not possible at present because the observed increase in the proportion of such storms appears to be larger than suggested by either theoretical or modeling studies and because of inadequate process knowledge, insufficient understanding of natural variability, uncertainty in modeling intense cyclones and uncertainties in historical tropical cyclone data.

5(b) Attribution of observed changes in physical and biological systems

In addition to attributing the observed changes in average global- and continental-scale temperature and other climate variables to anthropogenic GHG forcing, a similar attribution can be made between anthropogenic GHG forcing and observed changes in physical systems (e.g., melting glaciers) and

³⁰ Annular modes are preferred patterns of change in atmospheric circulation corresponding to changes in the zonally averaged mid-latitude westerly winds. The Northern Annular Mode has a bias to the North Atlantic and has a large correlation with the North Atlantic Oscillation (see footnote 36). The Southern Annular Mode occurs in the Southern Hemisphere.

biological systems and species (e.g., geographic shift of species) which are shown to change as a result of recent warming.

This section includes the observed changes in physical and biological systems in North America and in other parts of the world.

The IPCC (2007b) concluded that, "Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases." Furthermore, the IPCC states that, "A global assessment of data since 1970 has shown it is likely that anthropogenic warming has had a discernible influence on many physical and biological systems." As detailed above in Section 5(a), recent warming of the last 50 years is very likely the result of the accumulation of anthropogenic GHGs in the atmosphere.

Climate variability and non-climate drivers (e.g., land-use change, habitat fragmentation) need to be considered in order to make robust conclusions about the role of anthropogenic climate change in affecting biological and physical systems. IPCC (Rosenzweig et al. 2007) reviewed a number of joint attribution studies that linked responses in some physical and biological systems directly to anthropogenic climate change using climate, process, and statistical models. The conclusion of these studies is that "the consistency of observed significant changes in physical and biological systems and observed significant warming across the globe likely cannot be explained entirely due to natural variability or other confounding non-climate factors (Rosenzweig et al. 2007)."

The physical systems undergoing significant change include the cryosphere (snow and ice systems), hydrological systems, water resources, coastal zones and the oceans. These effects (reported with high confidence by IPCC (Rosenzweig et al. 2007)) include ground instability in mountain and permafrost regions, shorter travel season for vehicles over frozen roads in the Arctic, enlargement and increase of glacial lakes in mountain regions and destabilization of moraines damming these lakes, changes in Arctic flora and fauna including the sea-ice biomes and predators higher in the food chain, limitations on mountain sports in lower-elevation alpine areas, and changes in indigenous livelihoods in the Arctic.

Regarding biological systems, the IPCC (Rosenzweig et al. 2007) reports with very high confidence that the overwhelming majority of studies of regional climate effects on terrestrial species reveal trends consistent with warming, including poleward and elevational range shifts of flora and fauna, the earlier onset of spring events, migration, and lengthening of the growing season, changes in abundance of certain species, including limited evidence of a few local disappearances, and changes in community composition.

Human system responses to climate change are more difficult to identify and isolate due to the larger role that non-climate factors play (e.g., management practices in agriculture and forestry, and adaptation responses to protect human health against adverse climatic conditions).

Section 6

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Projected Future Greenhouse Gas Concentrations and Climate Change

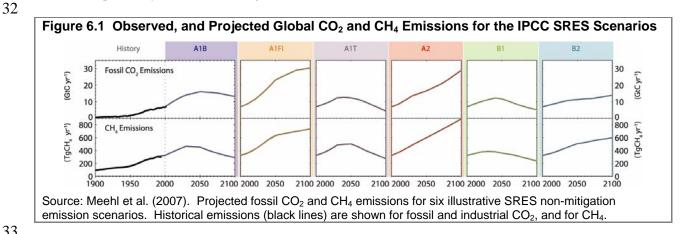
According to the IPCC (2007d), "continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely³¹ be larger than those observed during the 20th century." This section describes future GHG emission scenarios, the associated changes in atmospheric concentrations and radiative forcing, and the resultant changes in temperature, precipitation and sea level at global and U.S. scales. All future GHG emission scenarios described in this section assume no new explicit GHG mitigation policies -neither in the U.S. nor in other countries -- beyond those which were already enacted at the time the scenarios were developed. Future risks and impacts associated with the climate change projections are addressed in Part IV for domestic impacts and Part V for international impacts.

Global emission scenarios and associated changes in concentrations and radiative forcing **6(a)**

Greenhouse Gas Emissions

As described in Section 4(a), a number of different GHGs and other factors, including aerosols, cause radiative forcing changes and thus contribute to climate change. This section discusses the range of published global reference (or baseline) future emission projections for which no explicit GHG mitigation policies beyond those currently enacted are assumed.

The IPCC's most recent future climate change projections from the Fourth Assessment Report (2007) (discussed in Section 6(b) below) are based on the GHG emission scenarios from the IPCC Special Report on Emission Scenarios (IPCC, 2000). Box 6.1 provides background information on the different SRES emission scenarios. The SRES developed a range of long-term (out to the year 2100) global reference scenarios for the major GHGs directly emitted by human activities and for some aerosols. The IPCC SRES scenarios do not explicitly account for implementation of the Kyoto Protocol. Figure 6.1 presents the global IPCC SRES projections for the two most significant anthropogenic GHGs: CO₂ emissions primarily from the burning of fossil fuels, and CH₄ emissions.



³¹ According to IPCC terminology, "very likely" conveys a 90 to 99% probability of occurrence. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

Box 6.1: IPCC Reference Case Emission Scenarios from the Special Report on Emission Scenarios

- **A1.** The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).
- **A2.** The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.
- **B1.** The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.
- **B2.** The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

Box 6.2: CCSP Reference Case Emission Scenarios from Synthesis and Assessment Product 2.1

The scenarios in this report were developed using three integrated assessment models (IAMs). These models integrate socioeconomic and technological determinants of the emissions of GHGs with models of the natural science of Earth system response, including the atmosphere, oceans, and terrestrial biosphere. The three IAMs used are:

- The Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change.
- The Model for Evaluating the Regional and Global Effects (MERGE) of GHG reduction policies developed jointly at Stanford University and the Electric Power Research Institute.
- The MiniCAM Model of the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland. The MiniCAM model was also used to generate IPCC SRES scenarios.

Each modeling group produced a reference scenario under the assumption that no climate policies are imposed beyond current commitments, namely the 2008-12 first period of the Kyoto Protocol and the U.S. goal of reducing GHG emissions per unit of its gross domestic product by 18% by 2012. The resulting reference cases are not predictions or best-judgment forecasts but scenarios designed to provide clearly defined points of departure for studying the implications of alternative stabilization goals. The modeling teams used model input assumptions they considered *meaningful and plausible*. The resulting scenarios provide insights into how the world might evolve without additional efforts to constrain GHG emissions, given various assumptions about principal drivers of these emissions such as population increase, economic growth, land and labor productivity growth, technological options, and resource endowments.

The main drivers of emissions are population, economic growth, technological change, and land-use activities including deforestation. The detailed underlying assumptions (including final and primary energy by major fuel types) across all scenarios, and across all modeling teams that produced the scenarios, can be found in IPCC (2000). The range of GHG emissions in the scenarios widen over time to reflect uncertainties in the underlying drivers. Similar future GHG emissions can result from different socio-economic developments. The IPCC (2000) SRES report did not assign probabilities or likelihood to the scenarios, as it was stated that there is no single most likely, central, or best-guess scenario, either with respect to SRES scenarios or to the underlying scenario literature. This is why IPCC (2000) has recommended using range of SRES scenarios with a variety of underlying assumptions for use in analysis.

Despite the range in future emission scenarios, the majority of all reference-case scenarios project an increase of GHG emissions across the century, and show that CO₂ remains the dominant GHG over the course of the 21st century. Total *cumulative* (1990 to 2100) CO₂ emissions across the SRES scenarios range from 2,826 gigatonnes of CO₂ (GtCO₂) (or 770 GtC) to approximately 9,322 GtCO₂ (or 2,540 GtC).³² The 90th percentile range in 2100 for *annual* CO₂ emissions is 17 to 135 GtCO₂ (compared to about 34 GtCO₂ emitted in 2000).

Since the IPCC SRES (2000), new scenarios in the literature have emerged. The emission scenario range from the recent literature is similar to the range from the IPCC SRES. Studies since SRES used lower values for some drivers for emissions, notably population projections. However, for those studies incorporating these new population projections, changes in other drivers, such as economic growth, resulted in little change in overall emission levels (IPCC, 2007c).

For comparison, Figure 6.2 provides global projections of CO₂ emissions from the burning of fossil fuels and industrial sources from the three reference-case scenarios

Figure 6.2: Projected Global Emissions of CO₂ from Fossil Fuels and Industrial Sources across CCSP Reference Scenarios GtC/yr MERGE REF = IGSM REF -

Source: CCSP (2007b). Global emissions of CO_2 from fossil fuel combustion and other industrial sources, mainly cement production, increase over the century in all three reference scenarios. By 2100 emissions reach 22.5 GtC/yr 24.0 GtC/yr.

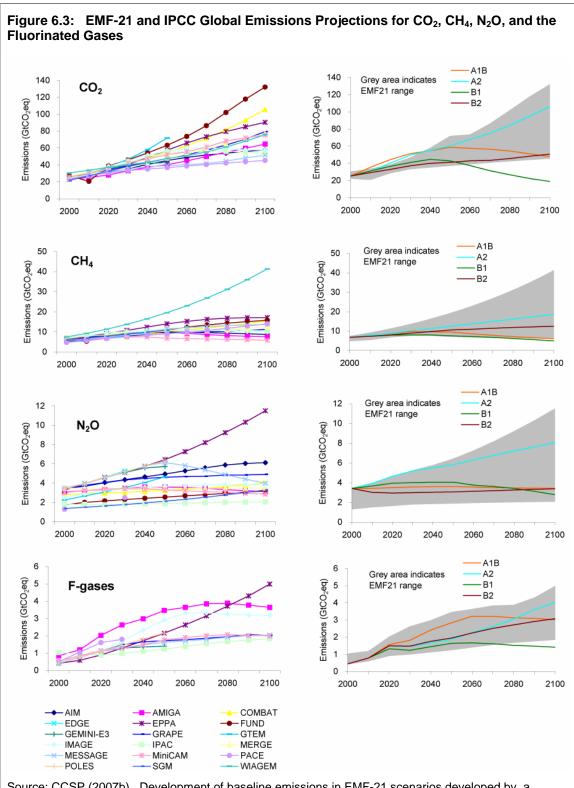
developed by the U.S. Climate Change Science Program (CCSP, 2007b). Box 6.2 provides background information on the reference case scenarios developed by the CCSP. The CCSP scenarios, because they were developed more recently than the IPCC SRES scenarios, do account for the implementation of the Kyoto Protocol for participating countries, but no explicit GHG mitigation policies beyond the Kyoto Protocol. The emissions in 2100 are approximately 88 GtCO₂ (24 GtC). This level of emissions is above the post-SRES IPCC median of 60 GtCO₂ (16 GtC), but well within the 90th percentile of the IPCC range.

 $^{^{32}}$ 1 Gigatonne (Gt) = 1 billion metric tons.

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the range found in SRES.

Figure 6.3 illustrates reference case emission projections for CO₂, CH₄, N₂O, and the fluorinated gases in aggregate (HFCs, PFCs, and SF₆ or "F-gases"). The emissions projections in Figure 6.3 are from the 21st Study of Stanford University's Energy Modeling Forum on multigas mitigation (EMF-21; see de la Chesnaye and Weyant, 2006, as referenced by the IPCC (Fisher et al., 2007)). Eighteen models participated in the EMF-21 study and the emissions ranges in Figure 6.3 are representative of the literature. The broad ranges of EMF-21 emissions projections in Figure 6.3, especially for N₂O and the F-gases, illustrate the uncertainties in projecting these future emissions, which is generally consistent with

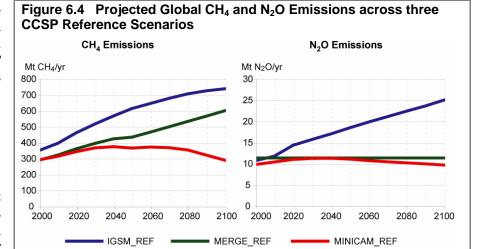


Source: CCSP (2007b). Development of baseline emissions in EMF-21 scenarios developed by a number of different modeling teams (left) and a comparison between EMF-21 and SRES scenarios (right) from DelaChesnaye and Weyant (2006), see also Van Vuuren et al. (2006b).

For comparison, Figure 6.4 provides the global CH₄ and N₂O projections from the three U.S. CCSP reference-case scenarios (CCSP, 2007b).

Future Concentration and Radiative Forcing Changes

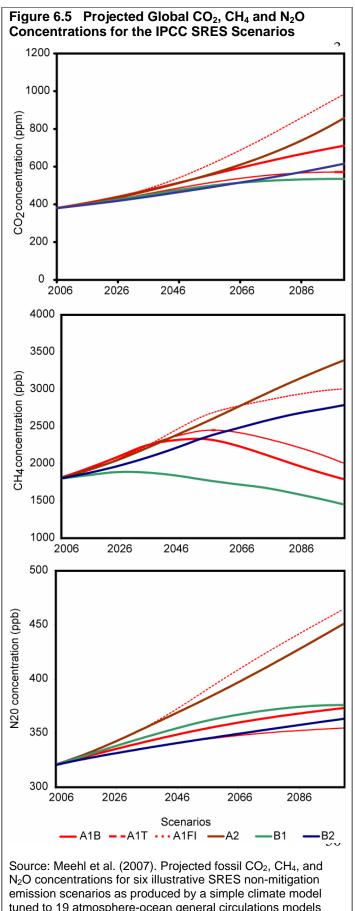
Figure 6.5 shows the latest IPCC projected increases in atmospheric CO_2 , CH_4 and N_2O concentrations for the SRES scenarios, and Figure 6.6 shows the associated radiative forcing for these CO_2 scenarios. In general, reference concentrations of CO_2 and



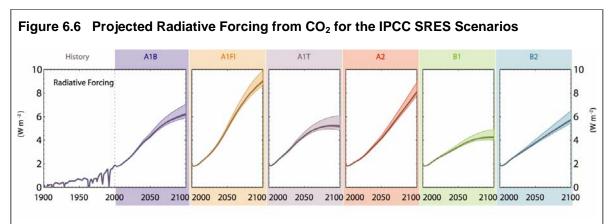
Source: CCSP (2007b). Global anthropogenic emissions of CH_4 and N_2O vary widely among the reference scenarios. There is uncertainty in year 2000 CH_4 emissions, with MIT's IGSM reference scenario ascribing more of the emissions to human activity and less to natural sources. Differences in scenarios reflect, to a large extent, different assumptions about whether current emissions rates will be reduced significantly for other reasons, for example, whether higher natural gas prices will stimulate capture of CH_4 for use as a fuel.

other GHGs are projected to increase. This is true even for those scenarios where annual emissions toward the end of the century are assumed to be lower than current annual emissions, due to the long atmospheric lifetimes of these gases. The CCSP scenarios show a similar picture of how atmospheric concentrations of the main GHGs and total radiative forcing change over time.

Carbon dioxide is projected to be the largest contributor to total radiative forcing in all periods and the radiative forcing associated with CO_2 is projected to be the fastest growing. The radiative forcing associated with the non- CO_2 GHGs is still significant and growing over time.



tuned to 19 atmosphere-ocean general circulations models (AOGCMs).



Source: Meehl et al. (2007). Projected radiative forcing from CO_2 for six illustrative SRES non-mitigation emission scenarios as produced by a simple climate model tuned to 19 AOGCMs. The lighter shaded areas depict the change in this uncertainty range, if carbon cycle feedbacks are assumed to be lower or higher than in the medium setting.

6(b) Projected changes in global temperature, precipitation patterns and sea level rise

Using the emissions scenarios described in Section 6(a), computer models project future changes in temperature, precipitation and sea level at global and regional scales. According to the IPCC (Meehl at al., 2007):

"[C]onfidence in models comes from their physical basis, and their skill in representing observed climate and past climate changes. Models have proven to be extremely important tools for simulating and understanding climate, and there is considerable confidence that they are able to provide credible quantitative estimates of future climate change, particularly at larger scales. Models continue to have significant limitations, such as in their representation of clouds, which lead to uncertainties in the magnitude and timing, as well as regional details, of predicted climate change. Nevertheless, over several decades of model development, they have consistently provided a robust and unambiguous picture of significant climate warming in response to increasing greenhouse gases." 33

Confidence decreases in changes projected by global models at smaller scales. Many important small-scale processes cannot be represented explicitly in models, and so must be included in approximate form as they interact with larger-scale features (Randall et al., 2007³⁴). Some of the most challenging aspects of understanding and projecting regional climate changes relate to possible changes in the circulation of the atmosphere and oceans, and their patterns of variability (Christensen et al., 2007³⁵). Nonetheless, the IPCC (2007d) concluded that recent advances in regional-scale modeling lead to higher confidence in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation and some aspects of extremes and of ice.

Global Temperature

³³ A number of climate models are developed and run at academic institutions and government supported research laboratories in the U.S. and other countries. The IPCC helps coordinate modeling efforts to facilitate comparisons across models, and synthesizes results published by several modeling teams.

³⁴ Randall et al., 2007 refers to Chapter 8, "Climate Models and Their Evaluation" in IPCC's 2007 Fourth Assessment Report, Working Group I.

³⁵ Christensen et al., 2007 refers to Chapter 11, "Regional Climate Projections" in IPCC's 2007 Fourth Assessment Report, Working Group I.

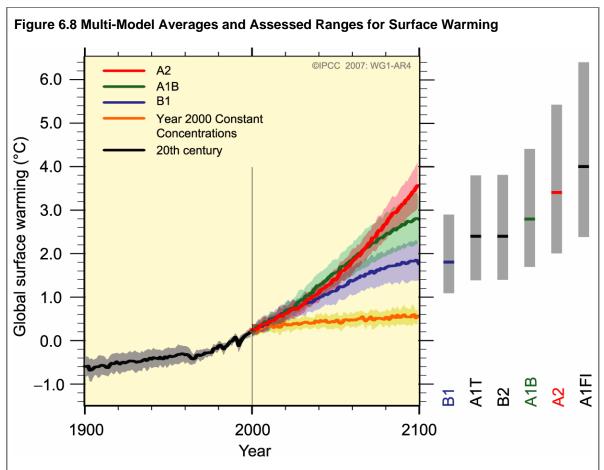
The latest IPCC assessment uses a larger number of simulations available from a broader range of models to project future climate relative to earlier assessments (IPCC, 2007d). All of the simulations performed by the IPCC project warming, for the full range of emissions scenarios.

For the next two decades, a warming of about 0.2°C (0.36°F) per decade is projected for a range of SRES emission scenarios (IPCC, 2007d). Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels (see the "Year 2000 Constant Concentrations" scenario in Figure 6.8), a further warming of about 0.1°C (0.18°F) per decade would be expected because of the time it takes for the climate system, particularly the oceans, to reach equilibrium (with year 2000 greenhouse gas levels). Through about 2030, the warming rate is affected little by different scenario assumptions or different assumptions about climate sensitivity (see Box 6.3), and is consistent with that observed for the past few decades. Possible future variations in natural forcings (e.g., a large volcanic eruption) could change these values somewhat (Meehl et al., 2007).

According to IPCC (see Figure 6.8), by mid-century (2046–2065), the choice of scenario becomes more important for the magnitude of the projected warming, with average values of 1.3°C (2.3°F), 1.8°C (3.2°F) and 1.7°C (3.1°F) from the models for scenarios B1 (low emissions growth), A1B (medium emissions growth) and A2 (high emissions growth), respectively (Meehl et al., 2007). About a third of that warming is projected to be due to climate change that is already committed (as shown in the "Year 2000 Constant Concentrations" scenario). By the 2090-2099 period (relative to the 1980-1999 range), projected warming varies significantly by emissions scenario. The full suite of SRES scenarios (given below) provides a warming range of 1.8°C to 4.0°C (3.2°F to 7.2°F) with an uncertainty range of 1.1°C to 6.4°C (2.0°F to 11.5°F). The multi-model average warming and associated uncertainty ranges for the 2090-2099 period (relative to 1980-1999) for each scenario, as illustrated in Figure 6.8 are:

<u>Scenario</u>	Average Global Warming by End of	Uncertainty Range
	Century Relative to ~1990	
B1	1.8°C (3.2°F)	1.1°C to 2.9°C (2.0°F to 5.2°F)
A1T	2.4°C (4.3°F)	1.4°C to 3.8°C (2.5°F to 5.7°F)
B2	2.4°C (4.3°F)	1.4°C to 3.8°C (2.5°F to 5.7°F)
A1B	2.8°C (5.0°F)	1.7°C to 4.4°C (3.1°F to 7.9°F)
A2	3.4°C (6.1°F)	2.0° C to 5.4° C (3.6° F to 9.7° F)
A1FI	+4.0°C (+7.2°F)	2.4°C to 6.4°C (4.3°F to 11.5°F)

The wide range of uncertainty in these estimates reflects the different assumptions about future concentrations of greenhouse gases and aerosols in the various scenarios considered by the IPCC and the differing climate sensitivities of the various climate models used in the simulations (NRC, 2001a).



Source: IPCC (2007d). Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.

Box 6.3: Climate Sensitivity

The sensitivity of the climate system to a forcing is commonly expressed in terms of the global mean temperature change that would be expected after a time sufficiently long for both the atmosphere and ocean to come to equilibrium with the change in climate forcing (NRC, 2001). Since IPCC's Third Assessment Report (IPCC, 2001b), the levels of scientific understanding and confidence in quantitative estimates of equilibrium climate sensitivity have increased substantially (Meehl et al. 2007). Basing their assessment on a combination of several independent lines of evidence, including observed climate change and the strength of known feedbacks simulated in general circulation models, the authors concluded that the global mean equilibrium warming for doubling CO_2 (a concentration of approximately 540 ppm), or 'equilibrium climate sensitivity', very likely greater than $1.5^{\circ}C$ ($2.7^{\circ}F$) and likely to lie in the range $2^{\circ}C$ to $4.5^{\circ}C$ ($3.6^{\circ}F$ to $8.1^{\circ}F$), with a most likely value of about $3^{\circ}C$ ($5.4^{\circ}F$). For fundamental physical reasons, as well as data limitations, the IPCC states a climate sensitivity higher than $4.5^{\circ}C$ cannot be ruled out, but that agreement for these values with observations and proxy data is generally worse compared to values in the $2-4.5^{\circ}C$ range (Meehl et al., 2007).

Stated and implied IPCC Climate Sensitivity Probabilities

Less than 1.5°C10% or less probability (stated)Less than 2.0°C5-17% probability (implied)2°C to 4.5°C66-90% probability (stated)Greater than 4.5°C5-17% probability (implied)

The overwhelming majority of the impacts literature assessed in IPCC analyzes the effects of warming for climate sensitivities within the most likely range (2-4.5°C), not at the tails of the distribution. As such, the effects information summarized in Chapter IV, Sections 6-14 of this document focuses on the plausible climate change effects assessed for climate sensitivities within the most likely range. Section 5(d) does address the state of knowledge pertaining to low probability effects of climate change that may be triggered by abrupt (non-linear) processes that become more likely at higher rates of climate forcing (NRC, 2002). However, abrupt climate change processes cannot be predicted with confidence and the thresholds linked to risks for social systems are at least as uncertain (Schneider et al., 2007).

Geographical patterns of projected warming show greatest temperature increases over land (roughly twice the global average temperature increase) and at high northern latitudes, and less warming over the southern oceans and North Atlantic, consistent with observations (see Section 4b) during the latter part of the 20th century (Meehl et al., 2007).

Global Precipitation

Models simulate that global mean precipitation increases with global warming (Meehl et al., 2007). However, there are substantial spatial and seasonal variations. Increases in the amount of precipitation are *very likely* in high latitudes, while decreases are *likely* in most subtropical land regions, continuing observed patterns in recent trends in observations.

Global Sea Level Rise

By the end of the century (2090-2099), sea level is projected by IPCC (2007d) to rise between 0.18 and 0.59 meters relative to the base period (1980-1999). These numbers represent the lowest and highest projections of the 5 to 95% ranges for all SRES scenarios considered collectively and include neither uncertainty in carbon cycle feedbacks nor rapid dynamical changes in ice sheet flow. In all scenarios, the average rate of sea level rise during the 21^{st} century very likely exceeds the 1961 to 2003 average rate (1.8 \pm 0.5 mm per year). Even if greenhouse gas concentrations were to be stabilized, sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks (IPCC, 2007d). Thermal expansion of ocean water contributes 70 to 75% of the central estimate for the rise in sea level for all scenarios (Meehl et al., 2007). Glaciers, ice caps and the Greenland Ice Sheet are also projected to add to sea level.

General Circulation Models indicate that the Antarctic Ice Sheet will receive increased snowfall without experiencing substantial surface melting, thus gaining mass and reducing sea level rise according to IPCC (Meehl et al., 2007). However, Meehl et al. (2007) note further accelerations in ice flow of the kind recently observed in some Greenland outlet glaciers and West Antarctic ice streams could substantially increase the contribution from the ice sheets, a possibility not reflected in the projections above. For example, if ice discharge from these processes were to increase in proportion to global average surface temperature change, it would add 0.1 to 0.2 m to the upper bound of sea level rise by 2090 to 2099. Dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise. Understanding of these processes is limited and there is no consensus on their magnitude.

Sea level rise during the 21st century is projected by IPCC to have substantial geographic variability due to factors that influence changes at the regional scale, including changes in ocean circulation or atmospheric pressure, and geologic processes (Meehl et al., 2007). The patterns in different models are not generally similar in detail, but have some common features, including smaller than average sea level rise in the Southern Ocean, larger than average sea level rise in the Arctic, and a narrow band of pronounced sea level rise stretching across the southern Atlantic and Indian Oceans.

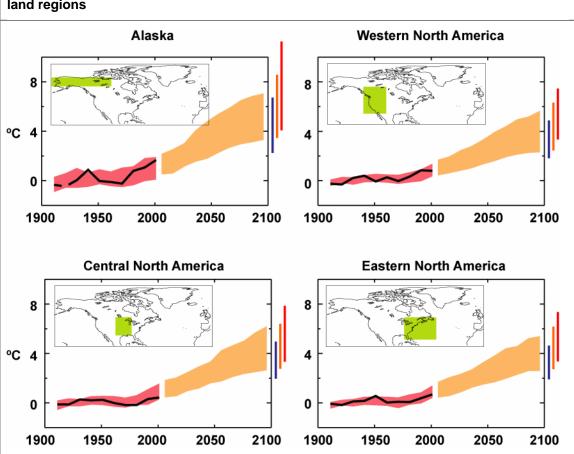
6(c) Projected changes in U.S. temperature, precipitation patterns, sea level rise

IPCC's AR4 includes projections for changes in temperature, precipitation and sea level rise for North America -- which can be generalized for the U.S - as well as some U.S. specific information. These projections are summarized in this section.

U.S. Temperatures

According to the IPCC, all of North America is very likely to warm during this century as shown in Figures in 6.9 and 6.10, and warm more than the global mean warming in most areas (Christensen et al., 2007). For scenario A1B (moderate emissions growth), the largest warming is projected to occur in winter over northern parts of Alaska, reaching 10°C (18°F) in the northernmost parts as shown in Figure 5.12, due to the positive feedback from a shorter season of snow cover. In western, central and eastern regions of North America, the projected warming has less seasonal variation and is not as large, especially near the coast, consistent with less warming over the oceans. The average warming in the U.S. is projected by nearly all the models used in the IPCC assessment to exceed 2°C (3.6°F), with 5 out of 21 models projecting average warming in excess of 4°C (7.2°F).

Figure 6.9: Temperature anomalies with respect to 1901 to 1950 for four North American land regions



Source: Christensen et al. (2007). Temperature anomalies with respect to 1901 to 1950 for four North American land regions for 1906 to 2005 (black line) and as simulated (red envelope) by multi-model dataset (MMD) models incorporating known forcings; and as projected for 2001 to 2100 by MMD models for the A1B scenario (orange envelope). The bars at the end of the orange envelope represent the range of projected changes for 2091 to 2100 for the B1 scenario (blue), the A1B scenario (orange) and the A2 scenario (red). The black line is dashed where observations are present for less than 50% of the area in the decade concerned.

Source: Christensen et al. (2007). Top row: Annual mean, December-January-February, and June-July-August temperature between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Bottom row: same as top, but for fractional change in precipitation.

U.S. Precipitation

A widespread increase in annual precipitation is projected by IPCC over most of the North American continent except the south and south-western part of the U.S. and over Mexico largely consistent with trends in recent decades (as described in Section 4) (Christensen et al., 2007). The largest increases are projected over northern North America (i.e. Canada and Alaska) associated with a poleward shift in storm tracks where precipitation increases by the largest amount in autumn and by the largest fraction in winter as shown in Figure 6.10. In western North America, modest changes in annual mean precipitation are projected, but the majority of models indicate an increase in winter and a decrease in summer. Models show greater consensus on winter increases to the north and on summer decreases to the south. These decreases are consistent with enhanced subsidence and flow of drier air masses in the southwest U.S. and northern Mexico. Accordingly, some models project drying in the southwest U.S., with more than 90% of the models projecting drying in northern and particularly western Mexico. On the windward slopes of

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the mountains in the west, precipitation increases are likely to be enhanced due to orographic lifting³⁶. In the northeastern U.S., annual mean precipitation is very likely to increase.

U.S. Sea Level Rise

For North American coasts, emissions scenario A1B shows sea level rise values close to the global mean, with slightly higher rates in eastern Canada and western Alaska, and stronger positive anomalies in the Arctic. The projected rate of sea level rise off the low-lying U.S. South Atlantic and Gulf coasts is also higher than the global average. Vertical land motion from geologic processes may decrease (uplift) or increase (subsidence) the relative sea level rise at any site (Nicholls et al., 2007).

6(d) Cryosphere (Snow and Ice) projections, focusing on North America and the U.S.

Snow season length and snow depth are very likely to decrease in most of North America as illustrated in Figure 6.11, except in the northernmost part of Canada where maximum snow depth is likely to increase (Christensen et al., 2007). Widespread increases in thaw depth are projected over most permafrost regions globally (IPCC, 2007d).

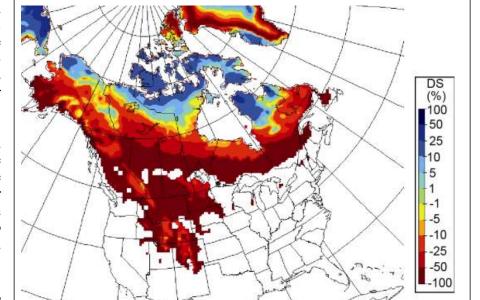
Figure 6.11 Percent Snow Depth Changes in March

Sea ice is projected to shrink in both the Arctic and the Antarctic under all SRES scenarios (IPCC, 2007d). In some projections, arctic latesummer sea ice disappears almost entirely by the latter part of the 21st century.

As the climate warms, glaciers and ice caps lose mass owing to dominance of summer melting over winter precipitation increases, contributing to sea level rise (Meehl et al., 2007).

6(e) Extreme events, focusing on North America and the U.S.

Models suggest that the human-induced climate change is expected to alter the prevalence and severity of many extreme events such as heat waves, cold waves, storms, floods, and



Source: Christensen et al. (2007). Percent snow depth changes in March (only calculated where climatological snow amounts exceed 5mm of water equivalent), as projected by the Canadian Regional Climate Model (CCRM; Plummer et al., 2006), driven by the Canadian General Circulation Model (CGCM), for 2041 to 2070 under SRES A2 compared to 1961 to 1990.

³⁶ Orographic lifting is defined as the ascent of air from a lower elevation to a higher elevation as it moves over rising terrain

droughts. This section describes IPCC's projections for extreme events focusing on North America and the U.S.; Sections 7-14 summarize some of the sectoral impacts of extreme events for the U.S.

Temperature

According to the IPCC, it is very likely that heat waves will become more intense, more frequent, and longer lasting in a future warm climate, whereas cold episodes are projected to decrease significantly. (Meehl, G.A. et al., 2007). Meehl and Tebaldi (2004; in Meehl et al., 2007) find that the pattern of future changes in heat waves, with greatest intensity increases over western Europe, the Mediterranean and the southeast and western U.S., is related in part to circulation changes resulting from an increase in greenhouse gases.

The IPCC cites a number of studies that project changes in temperature extremes in the U.S. (Christensen et al., 2007). Diffenbaugh et al. (2005) find that the frequency and the magnitude of extreme temperature events changes dramatically under a high-end emission scenario (SRES A2), with increases in extreme hot events and decreases in extreme cold events. Bell et al. (2004; in Christensen et al., 2007) examine changes in temperature extremes in their simulations centered on California and find increases in extreme temperature events, prolonged hot spells and increased diurnal temperature range. Leung et al. (2004; in Christensen et al., 2007) find increases in diurnal temperature range in six-subregions of the western U.S. in summer.

Possible implications for human health of these projected changes in temperature extremes are discussed in Section 7(b).

Precipitation and Storms

Intensity of precipitation events is projected to increase, particularly in tropical and high latitude areas that experience increases in mean precipitation (Meehl, G.A. et al., 2007). Even in areas where mean precipitation decreases (most subtropical and mid-latitude regions), precipitation intensity is projected to increase but there would be longer periods between rainfall events. Meehl et al. (2007) note that increases in heavy precipitation events have been linked to increases in flooding.

The IPCC projects a tendency for drying in mid-continental areas during summer, indicating a greater risk of droughts in those regions (Meehl et al., 2007). Extreme drought increases from 1% of present-day land area to 30% by the end of the century in the A2 (high emissions growth) scenario (Burke et al., 2006 in Meehl et al., 2007).

Several regional studies in the IPCC project changes in precipitation extremes in parts of the U.S ranging from a decrease in heavy precipitation in California (Bell et al., 2004 in Christensen et al., 2007) to an increase during winter in the northern Rockies, Cascades and Sierra Nevada mountain ranges (Leung et al., 2005 in Christensen et al., 2007). For the contiguous U.S., Diffenbaugh et al. (2005 in Christensen et al., 2007) find widespread increases in extreme precipitation events under SRES A2 (high emissions growth).

Based on a range of models, it is likely that tropical cyclones (typhoons and hurricanes) will become more intense, with stronger peak winds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures (IPCC, 2007d). Some modeling studies have projected a decrease in the number of tropical cyclones globally due to increased stability of the tropical atmosphere in a warmer climate, characterized by fewer weak storms and greater numbers of intense storms. A number of modeling studies have also projected a general tendency for more intense but fewer storms outside the

tropics, with a tendency towards more extreme wind events and higher ocean waves in several regions associated with these deepened cyclones (Meehl et al., 2007).

Possible implications of extreme precipitation events in the U.S. for health are described in Chapter 7, for food production and agriculture in Section 9, for water resources in Section 11, for coastal areas in Section 12, and for ecosystems and wildlife in Section 14.

6(f) Abrupt Climate Change

Abrupt climate change refers to sudden (on the order of decades), large changes in some major component of the climate system, with rapid, widespread effects. Abrupt climate changes are an important consideration because, if triggered, they could occur so quickly and unexpectedly that human or natural systems would have difficulty adapting to them (NRC, 2002). Potential abrupt climate change implications in the U.S. are not discussed in the sections 7 through 14 (the U.S. sectoral impacts) because they cannot be predicted with confidence, particularly for specific regions. This section therefore focuses on the general risks of abrupt climate change globally, with some discussion of potential regional implications where information is available.

 According to the National Research Council (2002): "Technically, an abrupt climate change occurs when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause." Crossing systemic thresholds may lead to large and widespread consequences (Schneider et al., 2007³⁷). The triggers for abrupt climate change can be forces that are external and/or internal to the climate system including (NRC, 2002):

- changes in the Earth's orbit³⁸
- a brightening or dimming of the sun
- melting or surging ice sheets
- strengthening or weakening of ocean currents
- emissions of climate-altering gases and particles into the atmosphere

More than one of these triggers can operate simultaneously, since all components of the climate system are linked.

 Scientific data show that abrupt changes in the climate at the regional scale have occurred throughout history and are characteristic of the Earth's climate system (NRC, 2002). During the last glacial period, abrupt regional warmings (likely up to 16°C within decades over Greenland) and coolings occurred repeatedly over the North Atlantic region (Jansen et al., 2007³⁹). These warmings likely had some large-scale effects such as major shifts in tropical rainfall patterns and redistribution of heat within the climate system but it is unlikely that they were associated with large changes in global mean surface temperature.

The National Research Council concluded that anthropogenic forcing may increase the risk of abrupt climate change (NRC, 2002):

³⁷ Schneider et al., 2007 citation refers to Chapter 19, "Assessing key vulnerabilities and the risk from climate change" in IPCC's 2007 Fourth Assessment Report, Working Group II.

³⁸ According to the National Research Council (2002), changes in the Earth's orbit occur too slowly to be prime movers of abrupt change but might determine the timing of events. Abrupt climate changes of the past were especially prominent when orbital processes were forcing the climate to change during the cooling into and warming out of ice ages (NRC, 2002).

³⁹ Jansen et al., 2007 refers to Chapter 6, "Palaeoclimate" in IPCC's 2007 Fourth Assessment Report, Working Group I.

"...greenhouse warming and other human alterations of the Earth system may increase the possibility of large, abrupt, and unwelcome regional or global climatic events. The abrupt changes of the past are not fully explained yet, and climate models typically underestimate the size, speed, and extent of those changes. Hence, future abrupt changes cannot be predicted with confidence, and climate surprises are to be expected."

Changes in weather patterns (sometimes referred to as weather regimes or natural modes) can result from abrupt changes that might occur spontaneously due to dynamical interactions in the atmosphere-ice-ocean system, or from the crossing of a threshold from slow external forcing (as described above) (Meehl et al., 2007). In a warming climate, changes in the frequency and amplitudes of these patterns might not only evolve rapidly, but also trigger other processes that lead to abrupt climate change (NRC, 2002). Examples of these patterns include the El Niño Southern Oscillation (ENSO)⁴⁰ and the North Atlantic Oscillation/Arctic Oscillation (NAO/OA).

Scientists have investigated the possibility of an abrupt slowdown or shutdown of the Atlantic meridional overturning circulation (MOC) triggered by greenhouse gas forcing. The MOC transfers large quantities of heat to the North Atlantic and Europe so an abrupt change in the MOC could have important implications for the climate of this region (Meehl et al., 2007). However, according to Meehl et al. (2007), the probability of an abrupt change in (or shutdown of) the MOC is low: "It is very unlikely that the MOC will undergo a large abrupt transition during the 21st century. Longer-term changes in the MOC cannot be assessed with confidence." The slowdown in the MOC projected by most models is gradual, so the resulting decrease in heat transport to the North Atlantic and Europe would not be large enough to reverse the warming that results from the increase in greenhouse gases.

The rapid disintegration of the Greenland Ice Sheet (GIS), which would raise sea levels 7 meters, is another commonly discussed abrupt change. Although models suggest the complete melting of the GIS would only require sustained warming in the range 1.9°C to 4.6°C (relative to the pre-industrial temperatures), it is expected to be a slow process that would take many hundreds of years to complete (Meehl et al., 2007).

A collapse of the West Antarctic Ice Sheet (WAIS), which would raise seas 5-6 meters, has been discussed as a low probability, high impact response to global warming (NRC, 2002; Meehl et al., 2007). The weakening or collapse of ice shelves, caused by melting on the surface or by melting at the bottom by a warmer ocean, might contribute to a potential destabilization of the WAIS. Recent satellite and in situ observations of ice streams behind disintegrating ice shelves highlight some rapid reactions of ice sheet systems (Lemke et al., 2007). Ice sheet models are only beginning to capture the small-scale dynamical processes that involve complicated interactions with the glacier bed and the ocean at the perimeter of the ice sheet (Meehl et al., 2007). These processes are not represented in the models used by IPCC to project sea level rise which suggest Antarctica will gain mass due to the likelihood of increasing snowfall, (although recent studies find no significant continent-wide trends in accumulation over the past several

⁴⁰ ENSO describes the full range of the Southern Oscillation (see-saw of atmospheric mass or pressure between the Pacific and Indo-Australian areas) that includes both sea surface temperature (SST) increases as well as SST decreases when compared to a long-term average. It has sometimes been used by scientists to relate only to the broader view of El Niño or the warm events, the warming of SSTs in the central and eastern equatorial Pacific. The acronym, ENSO, is composed of El Niño-Southern Oscillation, where El Niño is the oceanic component and the Southern Oscillation is the atmospheric component of the phenomenon.

⁴¹ The North Atlantic Oscillation (NAO) is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and much into Northern Asia. The NAO is a large scale seesaw in atmospheric mass or pressure between the subtropical high and the polar low. Similarly, the Arctic Oscillation (AO) refers to opposing atmospheric pressure patterns in northern middle and high latitudes. The NAO and AO are different ways of describing the same phenomenon.

decades; Lemke et al., 2007), reducing sea level rise. But it is possible that acceleration of ice discharge could become dominant, causing a net positive contribution. Given these competing factors, there is presently no consensus on the long-term future of the WAIS or its contribution to sea level rise (Meehl et al., 2007).

6(g) Effects on/from Stratospheric Ozone

Substances that deplete stratospheric ozone, which protects the Earth's surface from much of the sun's biologically harmful ultraviolet radiation, are regulated under Title VI of the Clean Air Act. According to the World Meteorological Organization (2007), climate change that results from changing greenhouse gas concentrations will affect the evolution of the ozone layer through changes in chemical transport, atmospheric composition, and temperature. In turn, changes in the stratospheric ozone can have implications for the weather and climate of the troposphere. The coupled interactions between the changing climate and ozone layer are complex and scientific understanding is incomplete (WMO, 2007). Specific information on climate change effects on/from stratospheric ozone in the U.S. has not been assessed. Except where indicated, the findings in this section apply generally to the globe with a focus on polar regions.

Effects of Elevated Greenhouse Gas Concentrations on Stratospheric Ozone

The World Meteorological Organization's (WMO) 2006 Scientific Assessment of Ozone Depletion (2007) concluded that future concentrations of stratospheric ozone are sensitive to future levels of the well-mixed greenhouse gases. According to the WMO (2007):

• Future increases of greenhouse gas concentrations, primarily CO₂, will contribute to the average cooling in the stratosphere. Stratospheric cooling is expected to slow gas-phase ozone depletion reactions and increase ozone.

• Enhanced methane emission (from warmer and wetter soils) is expected to enhance ozone production in the lower stratosphere.

• An increase in nitrous oxide emissions is expected to reduce ozone in the middle and high stratosphere.

 Two-dimensional models that include coupling between all of these well-mixed greenhouse gases and temperature project that ozone levels between 60° S and 60° N will return to 1980 values up to 15 years earlier than in models that are uncoupled (Bodeker et al., 2007⁴²). The impact of stratospheric cooling on ozone might be the opposite in polar regions where cooling could cause increases in polar stratospheric clouds, which, given enough halogens, would increase ozone loss (Bodeker et al., 2007).

Concentrations of stratospheric ozone are also sensitive to stratospheric water vapor concentrations which may remain relatively constant or increase (Baldwin et al., 2007). Increases in water vapor would cause increases in hydrogen oxide (HO_x) radicals, affecting ozone loss processes (Baldwin et al., 2007). Several studies (Dvortsov and Solomon, 2001; Shindell, 2001) cited in Baldwin et al. (2007) suggest increasing stratospheric water vapor would delay ozone layer recovery. Increases in stratospheric water vapor could also increase spring-time ozone depletion in the polar regions by raising the temperature threshold for the formation of polar stratospheric clouds (WMO, 2007).

The possible effects of climate change on stratospheric ozone are further complicated by possible changes in climate dynamics. Climate change can affect temperatures, upper level winds and storm patterns

⁴² Bodeker et al., 2007 citation refers to Chapter 6, "The Ozone Layer in the 21st Century" in WMO's Scientific Assessment of Ozone Depletion, 2006.

which, in turn, impact planetary waves that affect the stratosphere (Baldwin et al., 2007). Changes in the forcing and propagation of planetary waves⁴³ in the polar winter are a major source of uncertainty for predicting future levels of Arctic ozone loss (Austin et al., 2003 in Baldwin et al., 2007).

Climate Change Effects from Stratospheric Ozone

The WMO (2007) found changes to the temperature and circulation of the stratosphere affect climate and weather in the troposphere. The dominant tropospheric response, simulated in models and identified in analyses of observations, comprises changes in the strength of mid-latitude westerly winds. The mechanism for this response is not well-understood.

Modeling experiments (that simulate observed changes in stratospheric ozone and combined stratospheric ozone depletion and GHG increases) also suggest that Antarctic ozone depletion, through its effects on the lower stratospheric vortex, has contributed to the observed surface cooling over interior Antarctica and warming of the Antarctic Peninsula, particularly in summer (Baldwin et al., 2007). While the physics of these effects are not well-understood, the simulated pattern of warming and cooling is a robust result seen in many different models, and well-supported by observational studies.

As the ozone layer recovers, tropospheric changes that have occurred as a result of ozone depletion are expected to reverse (Baldwin et al., 2007).

⁴³ A planetary wave is a large horizontal atmospheric undulation that is associated with the polar-front jet stream and separates cold, polar air from warm, tropical air.

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Sections 7 through 14 within Part IV that describe observed effects, risks and projected impacts of climate change within the U.S. rely heavily on the North America chapter of the IPCC Working Group II volume of the Fourth Assessment Report. Because this IPCC chapter often makes statements for North America as a whole rather than specifically for the U.S. or Canada, EPA asked the leading authors of that chapter to make a statement about the applicability of that chapter's major conclusions to the U.S. Their statement is provided here in Box IV.1

Box IV.1: Short statement on the relevance of the findings in IPCC AR4 chapter 14 (North America) to the United States, 21 September 2007

This is a statement prepared by Christopher Field and Linda Mortsch, Coordinating Lead Authors of chapter 14, based on the chapter contents. It has not been separately evaluated or approved by the IPCC.

The major conclusions in the IPCC AR4 Working Group II chapter on North America (chapter 14) all apply to the United States. While each of the issues has a spatial pattern that makes it more critical in some locations than in others, all of the topics and impacts discussed in the chapter are relevant to at least some locations in the United States.

Chapter 14 presents a balanced assessment, based on existing research, of key implications of climate change for North America. The findings on sensitivities, trends, impacts, adaptation and vulnerability associated with climate variability and climate change were drawn from a review and assessment of published references. The findings were framed for the North American context but they are also relevant at the Canadian and the U.S. scale, as research results from both countries were used to develop the conclusions. A wide range of examples documents sensitivity, impacts, vulnerability and adaptation in the United States. Specifically, the U.S. has been affected by weather-related extreme events, including hurricanes, floods, wildfires and drought. Even though the U.S. has high adaptive capacity, there are still vulnerable people, places and sectors. Trends in forest fires in the U.S. and Canada illustrate sensitivity of forest ecosystems to climate variability. The projected impacts of increasing numbers of wildfires and a longer wildfire season are relevant to both countries. The U.S. has an extensive, populated and developed coastline with substantial vulnerability to climate-related extreme events. In the future, impacts from rising sea level, storms, and storm-surge flooding are likely to increase; the Atlantic and Gulf coasts are vulnerable to more severe storm impacts. Current trends and sensitivities, plus projected impacts from climate-change scenarios, point to problems with water availability and quality in the snowpack-dominated western mountains, where warming will likely compound challenges from over-allocation of water resources. Hot temperatures and extreme weather are likely to cause increased adverse health impacts, including heatrelated mortality, pollution, storm-related fatalities and injuries, and infectious diseases. The potential impacts and need for countermeasures to reduce impacts are relevant to both countries. The built environment is also vulnerable to a changing climate, with impacts from, for example, more intense precipitation and permafrost melt. The long life spans of major infrastructure and the extended planning required for replacing infrastructure place a priority on incorporating climate change information into infrastructure design as an adaptation strategy. The U.S., with its large population and widespread development, has many people and extensive assets that may be exposed to potential impacts of climate change.

Section 7

Human Health

Warm temperatures and extreme weather already cause and contribute to adverse human health outcomes through heat-related mortality and morbidity, pollution, storm-related fatalities and injuries, and disease. In the absence of effective adaptation, these effects are likely to increase with climate change. Depending on progress in health care, infrastructure, technology and access, climate change could increase the risk of heat wave deaths, respiratory illness through exposure to aero-allergens and ozone (discussed in Section 8), and climate sensitive diseases (Parry et al., 2007⁴⁴). Studies in temperate areas (which would include large portions of the U.S.) have shown that climate change is projected to bring some benefits, such as fewer deaths from cold exposure. The balance of positive and negative health impacts will vary from one location to another, and will alter over time as temperatures continue to rise.

In its Third Assessment Report (TAR), the IPCC produced a number of key findings summarizing the likely climate change health effects in North America (which apply to the U.S.). These effects, which were reaffirmed in the IPCC Fourth Assessment Report, include (Field et al., 2007):

- Increased deaths, injuries, infectious diseases, and stress-related disorders and other adverse effects associated with social disruption and migration from more frequent extreme weather.
- Increased frequency and severity of heatwaves leading to more illness and death, particularly among the young, elderly and frail.
- Expanded ranges of vector-borne and tick-borne diseases in North America but with modulation by public health measures and other factors.

This section describes the literature on the impacts of climate change on human health in four areas: direct temperature effects, extreme events, climate sensitive diseases, and aero-allergens. Non-health related impacts of these areas are discussed in other sections of this document. The health impacts resulting from climate change effects on air quality are discussed in Section 8.

There are few studies which address the interaction effects of multi-sector climate impacts (they may be nonlinear) or of interactions between climate change health impacts and other kinds of local, regional, and global changes (Field et al., 2007). For example, climate change impacts on human health in urban areas will be compounded by aging infrastructure, maladapted urban form and building stock, urban heat islands, air pollution, population growth and an aging population.

7(a) Temperature Effects

According to IPCC (2007d), it is very likely⁴⁵ that there were warmer and fewer cold days and nights and warmer and more frequent hot days over most land areas during the late 20th century (see section 4(b)). It is virtually certain that these trends will continue during the 21st century (see Section 6(b)).

As a result of the projected warming, the IPCC projects increases in heat-related mortality and morbidity globally (including in the U.S.) (IPCC, 2007b). The projected warming is expected to result in fewer deaths due to reduced exposure to the cold. It is not clear whether reduced mortality from cold will be greater or less than increased heat-related mortality in the U.S. due to climate change.

⁴⁴ Parry et al., 2007 citation refers to the Technical Summary in IPCC's 2007 Fourth Assessment Report, Working Group II.

⁴⁵ According to IPCC terminology, "very likely" conveys a 90 to 99% probability of occurrence. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

Increased heat exposure

Heatwaves are associated with marked short-term increases in mortality (Confalonieri et al, 2007). Hot temperatures have also been associated with increased morbidity. Increased hospital admissions for cardiovascular disease and emergency room visits have been documented in parts of North America during heat events (Schwartz et al., 2004 in Field et al., 2007). The populations most vulnerable to hot temperatures are older adults, the chronically sick, the very young and the socially isolated (IPCC, 2007b).

Heat-related morbidity and mortality are projected to increase globally (including in the U.S.) (Confalonieri et al, 2007). Heat exposures vary widely, and current studies do not quantify the years of life lost due to high temperatures. Estimates of heat-related mortality attributable to climate change are reduced but not eliminated when assumptions about acclimatization and adaptation are included in models. There is some indication that populations in the U.S. became less sensitive to high temperatures over the period 1964 to 1988, in part, due to these factors (Davis et al., 2002; Davis et al., 2003; Davis et al., 2004 in Confalonieri et al, 2007). On the other hand, growing numbers of older adults will increase the size of the population at risk because of a decreased ability to thermo-regulate is a normal part of the aging process (Confalonieri et al, 2007). In addition, almost all the growth in population in the next 50 years is expected to occur in cities (Cohen, 2003 in Confalonieri et al, 2007) where temperatures tend to be higher due to the urban heat island effect increasing the total number of people at risk of adverse health outcomes from heat.

Across North America, the population over the age of 65 -- the segment of the population most at-risk of dying from heat waves -- will increase slowly to 2010, and then grow dramatically as the Baby Boomers age (Field et al., 2007). Severe heat waves are projected to intensify in magnitude and duration over the portions of the U.S. where these events already occur (high confidence). The IPCC documents the following U.S. regional scenario projections of increases in heat and/or heat-related effects (Confalonieri et al., 2007; Field et al., 2007):

• By the 2080s, in Los Angeles, number of heat wave days (at or above 32°C or 90°F) increases 4-fold under the B1 emissions scenario (low growth) and 6-8-fold under A1FI emissions scenario (high growth) (Hayhoe, 2004). Annual number of heat-related deaths in Los Angeles increases from about 165 in the 1990s to 319 to 1,182 for a range of emissions scenarios.

 • Chicago is projected to experience 25% more frequent heat waves annually by the period spanning 2080-2099 for a business-as-usual (A1B) emissions scenario (Meehl and Tebaldi, 2004).

Reduced cold exposure

Cold waves continue to be a problem in northern latitudes in temperature regions where very low temperatures can be reached in a few hours and extend over long periods (Confalonieri et al, 2007⁴⁷). Accidental cold exposure occurs mainly outdoors, among socially deprived people (alcoholics, the homeless), workers, and the elderly in temperate and cold climates (Ranhoff, 2000 in Confalonieri et al, 2007) but cold waves also affect health in warmer climates (EM-DAT, 2006 in Confalonieri et al, 2007). Living in cold environments in polar regions is associated with a range of chronic conditions in the non-indigenous population (Sorogin, 1993 in Confalonieri et al, 2007) with acute risk from frostbite and

⁴⁶ A heat island refers to urban air and surface temperatures that are higher than nearby rural areas. Many U.S. cities and suburbs have air temperatures up to 10°F (5.6°C) warmer than the surrounding natural land cover.

⁴⁷ Confalonieri et al., 2007 citation refers to Chapter 8, "Human Health" in IPCC's 2007 Fourth Assessment Report, Working Group II.

hypothermia (Hassi et al., 2005 in Confalonieri et al, 2007). In countries with populations well-adapted to cold conditions, cold waves can still cause substantial increases in mortality if electricity or heating systems fail (Confalonieri et al, 2007).

The IPCC projects reduced human mortality from cold exposure through 2100 (Confalonieri et al, 2007). It is not clear whether reduced mortality from cold will be greater or less than increased heat-related mortality in the U.S. due to climate change. Projections of cold-related deaths, and the potential for decreasing their numbers due to warmer winters, can be overestimated unless they take into account the effects of season as well as influenza, which is not strongly associated with monthly winter temperature (Armstrong et al., 2004 in Confalonieri et al, 2007; McMichael et al, 2001).

IPCC does not cite any studies since the TAR which project changes in both heat- and cold-related mortality in the U.S. for different climate scenarios⁴⁸. In the TAR, the IPCC cited several studies that indicate decreases in winter mortality may be greater than increases in summer mortality in some temperate countries under climate change (McMichael et al, 2001). However, it cites one U.S. study (Kalkstein and Greene, 1997) that estimates increases in heat-related deaths will be three times greater than decreases in cold-related deaths. Given the paucity of recent literature on the subject and the challenges in estimating and projecting weather-related mortality, IPCC concludes additional research is needed to understand how the balance of heat-and cold-related deaths might change globally under different climate scenarios (Confalonieri et al, 2007).

7(b) Extreme Events

In addition to the direct effects of temperature on heat and cold-related mortality, projected trends in climate change-related exposures of importance to human health will increase the number of people (globally, including in the U.S.) suffering from disease and injury due to floods, storms, droughts and fires (high confidence) (Confalonieri et al, 2007). Vulnerability to weather disasters depends on the attributes of the people at risk (including where they live, age, income, education, and disability) and on broader social and environmental factors (level of disaster preparedness, health sector responses, and environmental degradation).

Floods and storms

The IPCC projects a very likely increase in heavy precipitation event frequency over most areas as described in Sections 6(b and c). Increases in the frequency of heavy precipitation events are associated with increased risk of deaths and injuries as well as infectious, respiratory and skin diseases (IPCC, 2007b). Floods are low-probability, high-impact events that can overwhelm physical infrastructure, human resilience, and social organization (Confalonieri et al, 2007). Flood health impacts include deaths, injuries, infectious diseases, intoxications and mental health problems (Greenough et al., 2001; Ahern et al., 2005 in Confalonieri et al, 2007). Flooding may also lead to contamination of waters with dangerous chemicals, heavy metals, or other hazardous substances, from storage or from chemicals already in the environment (Confalonieri et al, 2007).

⁴⁸ Some have raised the issue of the observed trend in migration within the U.S. to the "Sunbelt" (particularly among older adults – for purposes including comfort, recreation and leisure as well as health) and what this implies about potential health benefits as a result of a warmer climate. Average climate warming may indeed provide health benefits in some areas; this point is captured in this section's statement about less cold-related mortality due to climate warming. These potential warming benefits are independent of the potential negative effects of extreme heat events.

The IPCC (2007d) also projects likely increases in intense tropical cyclone activity as described in Section 6(b). Increases in tropical cyclone intensity are linked to increases in the risk of deaths, injuries, water and foodborne diseases as well as post-traumatic stress disorders (IPCC, 2007b). Drowning by storm surge, heightened by rising sea levels and more intense storms (as projected by IPCC), is the major killer in coastal storms where there are large numbers of deaths (Confalonieri et al, 2007). High-density populations in low-lying coastal regions such as the U.S. Gulf of Mexico experience a high health burden from weather disasters, particularly among lower income groups. In 2005, Hurricane Katrina claimed over 1800 lives in the vicinity of the low-lying U.S. Gulf Coast and lower income groups were most affected (Graumann et al., 2005 in Nicholls et al.⁴⁹; Guidry and Margolis, 2005 in Confalonieri et al., 2007). While Katrina was a Category 3 hurricane and its path was forecast well in advance, there was a secondary failure of the levee system. This illustrates that multiple factors contribute to making a disaster and that adaptation measures may not fully avert adverse consequences. Additional information about U.S. vulnerability to the potential for more intense tropical cyclones can be found in Section 12(b).

Droughts

Areas affected by droughts are likely to increase according to IPCC (2007d) as noted in Section 6(e). The health impacts associated with drought tend to most affect semi-arid and arid regions, poor areas and populations, and areas with human-induced water scarcity; hence many of these effects are likely to be experienced in developing countries and not directly in the U.S. Information about the effects of increasing drought on U.S. agriculture can be found in section 9(c).

Forest Fires

In some regions, changes in the mean and variability of temperature and precipitation are projected to increase the frequency and severity of fire events, including in parts of the U.S. (Easterling, W. et al., 2007⁵⁰). Forest and bushfires cause burns, smoke inhalation and other injuries. Large fires are also accompanied by an increased number of patients seeking emergency services for inhalation of smoke and ash (Hoyt and Gerhart, 2004 in Confalonieri et al., 2007). The IPCC (Field et al., 2007) noted a number of observed changes in U.S. wildfire size and frequency. Additional information on the effects of forest fires can be found in Sections 8(b) and 10(b).

7(c) Climate-sensitive diseases

The IPCC (2007b) notes that many human diseases are sensitive to weather. The incidence of airborne infectious diseases (e.g., coccidioidomycosis) varies seasonally and annually, due partly to climate variations such as drought, which is projected to increase in North America (Kolivras and Comrie, 2003 in Field et al., 2007).

Waterborne disease outbreaks are distinctly seasonal (which suggests potential underlying environmental or weather control), clustered in particular watersheds, and associated with heavy precipitation. The risk of infectious disease following flooding in high-income countries is generally low, although increases in respiratory and diarrheal diseases have been reported after floods (Miettinen et al., 2001; Reacher et al., 2004; Wade et al., 2004 in Confalonieri et al, 2007). For example, after Hurricanes Katrina and Rita in 2005, contamination of water supplies with fecal bacteria led to many cases of diarrheal illness and some deaths (CDC, 2005; Manuel, 2006 in Confalonieri et al, 2007).

⁴⁹ Nicholls et al., 2007 citation refers to Chapter 6, "Coastal Systems and Low-lying Areas" in IPCC's 2007 Fourth Assessment Report, Working Group II.

⁵⁰ Easterling et al., 2007 citation refers to Chapter 5, "Food, Fibre and Forest Products" in IPCC's 2007 Fourth Assessment Report, Working Group II.

Foodborne diseases show some relationship with temperature (e.g., increased temperatures have been associated with increased cases of Salmonellosis) (D'Souza et al., 2004; Kovats et al., 2004; Fleury et al., 2006 in Confalonieri et al, 2007). *Vibrio* spp. infections from shellfish consumption may also be influenced by temperature (Wittmann and Flick, 1995; Tuyet et al., 2002 in Confalonieri et al, 2007). For example, the IPCC (Confalonieri et al, 2007) cited a 2004 outbreak of *V parahaemolyticus* that was linked to atypically high temperatures in Alaskan coastal waters (McLaughlin et al., 2005).

The sensitivity of many zoonotic⁵¹ diseases to climate fluctuations is also highlighted by the IPCC (Field et al., 2007). Above average temperatures in the U.S. during the summers of 2002-2004 were linked to the greatest transmissions of West Nile virus (Reisen et al., 2006 in Field et al., 2007). Saint Louis encephalitis has a tendency to appear during hot, dry La Nina years (Cayan et al., 2003 in Field et al., 2007). Associations between temperature (Ogden et al., 2004) and precipitation (McCabe and Bunnell, 2004) and tick-borne Lyme disease are also noted by IPCC (Field et al., 2007). A study found that the northern range limit of *Ixodes scapularis*, the tick that carries Lyme disease, could shift north by 200 km by the 2020s and 1000 km by the 2080s (Brownstein et al., 2003 in Field et al., 2007).

Although large portions of the U.S. may be at potential risk for diseases such as malaria based on the distribution of competent disease vectors, locally acquired cases have been virtually eliminated, in part due to vector and disease control activities (Confalonieri et al, 2007).

The IPCC concludes that human health risks from climate change will be strongly modulated by changes in health care, infrastructure, technology, and accessibility to health care (UNPD, 2005 in Field et al., 2007). The aging of the population and patterns of immigration and/or emigration will also strongly influence risks (UNPD, 2005 in Field et al., 2007). Infectious diseases could become more prominent if public health systems unravel or if new pathogens arise that are resistant to our current methods of disease control (Barrett et al., 1998 in Confalonieri et al, 2007).

7(d) Aeroallergens

Exposure to allergens results in allergenic illnesses in approximately 20% of the US population (American Academy of Allergy Asthma & Immunology (AAAAI), 1996-2006). Although there is substantial evidence suggesting a causal relationship between aeroallergens and allergenic illnesses, it remains unclear which aeroallergens are most important for sensitization and subsequent disease development (Nielsen, G. D. et al., 2002). Not only the type, but also the amount of aeroallergen to which an individual is exposed influences the development of an allergenic illness.

Climate change, including changes in CO₂ concentrations, could impact the production, distribution, dispersion and allergenicity of aeroallergens and the growth and distribution of weeds, grasses and trees that produce them (McMichael. et al., 2001⁵²; Confalonieri et al., 2007). These changes in aeroallergens and subsequent human exposures could affect the prevalence and severity of allergy symptoms. However, the scientific literature does not provide definitive data or conclusions on how climate change might impact aeroallergens and subsequently the prevalence of allergenic illnesses in the U.S. In addition, there are numerous other factors that affect aeroallergen levels and the prevalence of associated allergenic illnesses, such as changes in land use, air pollution, and adaptive responses, many of which are difficult to assess.

⁵¹A zoonotic disease is any infectious disease that is able to be transmitted from an animal or nonhuman species to humans. The natural reservoir is a nonhuman reservoir.

⁵² McMichael et al., 2001 citation refers to Chapter 4, "Human Health" in IPCC's 2001 Third Assessment Report, Working Group II.

It has generally been observed that the presence of elevated CO₂ concentrations and temperatures stimulates plants to increase photosynthesis, biomass, water use efficiency, and reproductive effort. The IPCC concluded that pollens are likely to increase with elevated temperature and CO₂ (Field et al., 2007). Laboratory studies that used a doubling of CO₂ stimulated ragweed-pollen production by over 50% (Wayne et al., 2002 in Field et al., 2007). A U.S.-based field study which used existing temperature/CO₂ concentration differences between urban and rural areas as a proxy for climate change found that ragweed grew faster, flowered earlier, and produced significantly greater aboveground biomass and ragweed pollen at urban locations than at rural locations (Ziska et al., 2003 in Field et al., 2007).

The IPCC (Confalonieri et al, 2007) noted that climate change has caused an earlier onset of the spring pollen season in North America (D'Amato et al., 2002; Weber, 2002; Beggs, 2004) and that there is limited evidence that the length of the pollen season has increased for some species. However, it is unclear whether the allergenic content of these pollens has changed. The IPCC concluded that introductions of new invasive plant species with high allergenic pollen present important health risks, noting that ragweed (*Ambrosia artemisiifolia*) is spreading in several parts of the world (Rybnicek and Jaeger, 2001; Huynen and Menne, 2003; Taramarcaz et al., 2005; Cecchi et al., 2006 in Confalonieri et al, 2007).

Section 8

Air Quality

The IPCC (2007b) projects with virtual certainty⁵³ "declining air quality in cities" due to "warmer and fewer cold days and nights and/or warmer/more frequent hot days and nights over most land areas" across all world regions. Furthermore, the IPCC reports with very high confidence that climate change impacts on human health in U.S. cities will be compounded by population growth and an ageing population (Field et al., 2007). Surface air concentrations of air pollutants are highly sensitive to winds, temperature, humidity and precipitation (Denman et al. 2007). Climate change can be expected to influence the concentration and distribution of air pollutants through a variety of direct and indirect processes, including the modification of biogenic emissions, the change of chemical reaction rates, wash out of pollutants by precipitation, and modification of weather patterns that influence pollutant buildup. In summarizing the impact of climate change on ozone and particulate matter (PM), the IPCC (Denman et al., 2007) states that "future climate change may cause significant air quality degradation by changing the dispersion rate of pollutants, the chemical environment for ozone and PM generation and the strength of emissions from the biosphere, fires and dust." The IPCC also states (Denman et al., 2007) that large uncertainties remain for many issues, so that quantitative estimates of the importance of the coupling mechanisms are not always available and, further, regional differences also limit our ability to provide a simple quantitative description of the interactions between biogeochemical processes and climate change.

This section describes how climate change may increase ambient concentrations of ozone and, in some cases, PM with associated impacts on public health and welfare in the U.S.

8(a) Tropospheric Ozone

According to the IPCC (Denman et al., 2007), climate change is expected to lead to increases in regional ozone pollution in the U.S. and other countries. Ozone impacts on pubic health and welfare are described in EPA's Air Quality Criteria Document for Ozone (EPA, 2006). Breathing ozone at sufficient concentrations can reduce lung function, thereby aggravating asthma or other respiratory conditions. Ozone exposure at sufficient concentrations has been associated with increases in respiratory infection susceptibility, medicine use by asthmatics, emergency department visits and hospital admissions. Ozone exposure may contribute to premature death, especially in susceptible populations. In contrast to human health effects, which are associated with short-term exposures,, the most significant ozone-induced plant effects (e.g., biomass loss, yield reductions) result from the accumulation of ozone exposures over the growing season, with differentially greater impact resulting from exposures to higher concentrations and/or longer durations.

Tropospheric ozone is both naturally occurring and, as the primary constituent of urban smog, a secondary pollutant formed through photochemical reactions involving nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the presence of sunlight. As described below, climate change can affect ozone by modifying (1) emissions of precursors, (2) atmospheric chemistry, and (3) transport and removal (Denman et al., 2007).

The IPCC (Denman et al., 2007) states that, for all world regions, "climate change affects the sources of ozone precursors through physical response (lightning), biological response (soils, vegetation, and biomass burning) and human response (energy generation, land use, and agriculture)." Nitrogen oxide

⁵³ According to IPCC terminology, "virtually certain" conveys a greater than 99% probability of occurrence. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

emissions due to lightning are expected to increase in a warmer climate (Denman et al., 2007). Additionally, studies using general circulation models concur that influx of ozone from the stratosphere to the troposphere could increase due to large-scale atmospheric circulation shifts (i.e., the Brewer-Dobson circulation) in response to climate warming (Denman et al., 2007). The sensitivity of microbial activity in soils to temperature also points toward a substantial increase in the nitric oxide emissions (Yienger and Levy 1995; Brasseur et al., 2006). As described below, biogenic VOC emissions increase with increasing temperature.

Climate induced changes of biogenic VOC emissions alone may be regionally substantial and cause significant increases in ozone concentrations (Hauglustaine et al., 2005; Hogrefe et al., 2004; European Commission, 2003). Sensitivity simulations for the 2050s, relative to the 1990s (under the A2 IPCC scenario) indicate that increased biogenic emissions alone add 1–3 parts per billion (ppb) to summertime average daily maximum 8-hour ozone concentrations in the Midwest and along the eastern seaboard (Hogrefe et al., 2004). The IPCC (Meehl et al., 2007) reports that biogenic emissions are projected to increase by between 27 and 59%, contributing to a 30 to 50% increase in ozone formation over northern continental regions (under the A2 IPCC scenario for the 2090-2100 timeframe, relative to 1990-2000).

Climate change impacts on temperature and water vapor could affect ozone chemistry significantly (Denman et al., 2007). A number of studies in the U.S. have shown that summer daytime ozone concentrations correlate strongly with temperature. That is, ozone generally increases at higher temperatures. This correlation appears to reflect contributions of comparable magnitude from (1) temperature-dependent biogenic VOC emissions, as mentioned above, (2) thermal decomposition of peroxyacetylnitrate (PAN), which acts as a reservoir for NOx, as described immediately below, and (3) association of high temperatures with regional stagnation, also discussed below (Denman et al., 2007).

Climate change is projected to increase surface layer ozone concentrations in both urban and polluted rural environments (any world region of high emissions) due to decomposition of PAN at higher temperatures (Sillman and Samson, 1995; Liao and Seinfeld, 2006). Warming enhances decomposition of PAN, releasing NOx, an important ozone precursor (Stevenson et al., 2005). Model simulations with higher temperatures for the year 2100 showed enhanced PAN thermal decomposition caused this species to decrease by up to 50% over source regions and ozone net production to increase (Hauglustaine et al., 2005).

Atmospheric circulation can be expected to change in a warming climate and, thus, modify pollutant transport and removal. If there are more frequent occurrences of stagnant air events in urban or industrial areas could enhance the intensity of air pollution events, although the importance of these effects is not yet well quantified (Denman et al., 2007). The IPCC (2007d) concluded that "extra-tropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation, and temperature patterns, continuing the broad pattern of observed trends over the last half-century."

The IPCC (Denman et al., 2007) cites the Mickley et al. (2004) study for the eastern U.S. which found an increase in the severity and persistence of regional pollution episodes due to the reduced frequency of ventilation by storms tracking across Canada. This study found that surface cyclone activity decreased by approximately 10–20% in a future simulation (for 2050, under the IPCC A1B scenario), which is in general agreement with a number of observational studies over the northern midlatitudes and North America (Zishka and Smith, 1980; Agee, 1991; Key and Chan, 1999; McCabe et al., 2001). Northeast U.S. summer pollution episodes are projected in this study to increase in severity and duration; pollutant concentrations in episodes increase 5-10% and episode durations increase from 2 to 3-4 days.

Regarding the role water vapor plays in tropospheric ozone formation, the IPCC (Denman et al., 2007) reports that simulations for the 21st century indicate a decrease in the lifetime of tropospheric ozone due

to increasing water vapor. The projected increase in water vapor both decelerates the chemical production and accelerates the chemical destruction of ozone (Meehl et al., 2007). Overall, the IPCC states that climate change is expected to decrease background tropospheric ozone due to higher water vapor and to increase regional and urban-scale ozone pollution due to higher temperatures and weaker air circulation (Denman et al., 2007; Confalonieri et al., 2007).

For North America, the IPCC (Field et al., 2007) reports that surface ozone concentration may increase with a warmer climate. Several studies predict increases in ozone concentrations due to climate change in the near future (2020s and 2030s) as well as for 2050 and beyond. The IPCC (Field et al., 2007; Wilbanks et al., 2007) cites Hogrefe et al. (2004) who evaluate the effects of climate change on regional ozone in 15 U.S. cities, finding that average summertime daily 8-hour maximum ozone concentrations could increase by 2.7 ppb in the 2020s and by 4.2 ppb in the 2050s (under the IPCC A2 scenario). For the 2050s (under the IPCC A2 scenario), the IPCC (Field et al., 2007) cites Bell et al. (2007) who report that the projected effects of climate change on ozone in 50 eastern U.S. cities increased the number of summer days exceeding the 8-hour U.S. EPA standard by 68% (Bell et al., 2007).

Mickley et al. (2004) found that significant changes occur at the high end of the pollutant concentration distribution (episodes) in the Midwest and Northeast between 2000 and 2050. Bell and Ellis (2004) also found the largest increases in ozone concentrations occurred near peak values. While summer average daily maximum 8-hour ozone concentrations increase by 2.7, 4.2, and 5.0 ppb in 2020s, 2050s, and 2080s (compared to 1990s), the fourth highest summertime daily maximum 8-hour ozone concentrations increase by 5.0, 6.4, and 8.2 ppb for the 2020s, 2050s, and 2080s, respectively (compared to 1990s) (Hogrefe et al., 2004). These findings raise particular health concerns.

The IPCC (Field et al., 2007) states that, "warming and climate extremes are likely to increase respiratory illness, including exposure to pollen and ozone." And the IPCC further states that "severe heat waves, characterized by stagnant, warm air masses and consecutive nights with high minimum temperatures will intensify in magnitude and duration over the portions of the U.S. and Canada, where they already occur (high confidence) (Field et al., 2007)."

Holding population, dose-response characteristics, and pollution prevention measures constant, ozone-related deaths from climate change in the U.S. are projected to increase by approximately 4.5% from the 1990s to the 2050s (under the IPCC A2 scenario) (Field et al., 2007; Bell et al., 2007; Knowlton et al., 2004). According to the IPCC (Field et al., 2007), the "large potential population exposed to outdoor air pollution, translates this small relative risk into a substantial attributable health risk." In New York City, health impacts could be further exacerbated by climate change interacting with urban heat island effects (Field et al., 2007).

The influence of climate change on air quality will play out against a backdrop of ongoing regulatory control of both ozone and particulate matter (PM) that will shift the baseline concentrations of these two important pollutants. However, most studies to date that have examined potential future climate change impacts on air quality isolate the climate effect by holding precursor air pollutant emissions constant over time.

The IPCC reports (Denman et al., 2007) that "the current generation of tropospheric ozone models is generally successful in describing the principal features of the present-day global ozone distribution." The IPCC (Denman et al., 2007) also states that "there are major discrepancies with observed long-term trends in ozone concentrations over the 20th century" and "resolving these discrepancies is needed to establish confidence in the models."

In addition to human health effects, elevated levels of tropospheric ozone has significant adverse effects on crop yields in the U.S. and other world regions, pasture and forest growth and species composition (Easterling et al., 2007; EPA, 2006; Volk et al., 2006; Ashmore, 2005; Vandermeiren, 2005; Loya et al., 2003). Furthermore, the effects of air pollution on plant function may indirectly affect carbon storage; recent research showed that tropospheric ozone resulted in significantly less enhancement of carbon sequestration rates under elevated CO₂ (Loya *et al.*, 2003), due to negative effects of ozone on biomass productivity and changes in litter chemistry (Booker *et al.*, 2005; Liu *et al.*, 2005).

8(b) Particulate Matter

Particulate matter impacts on public health and welfare are described in EPA's Air Quality Criteria Document for Particulate Matter (EPA, 2004). Particulate matter is a complex mixture of anthropogenic, biogenic and natural materials, suspended as aerosol particles in the atmosphere. When inhaled, the smallest of these particles can reach the deepest regions of the lungs. Scientific studies have found an association between exposure to PM and significant health problems, including: aggravated asthma; chronic bronchitis; reduced lung function; irregular heartbeat; heart attack; and premature death in people with heart or lung disease. Particle pollution also is the main cause of visibility impairment in the nation's cities and national parks.

The overall directional impact of climate change on PM levels in the U.S. remains uncertain. The body of literature specifically addressing the potential effects of climate change on PM is limited but there is a substantial body of literature describing how ambient PM responds to a wide range of meteorological conditions. On the basis of this information, broad conclusions can be drawn concerning the behavior of ambient PM concentrations given a set of the meteorological changes anticipated in a warming climate. Those meteorological changes are expected to affect PM concentrations by modifying emissions of (1) primary PM and PM precursor emissions, (2) aerosol photochemistry, and (3) transport and removal, as described below.

Particulate matter and PM precursor emissions are affected by climate change through physical response (wind blown dust), biological response (forest fires and vegetation type/distribution) and human response (energy generation). Most natural aerosol sources are controlled by climatic parameters like wind, moisture and temperature; thus, human induced climate change is expected to affect the natural aerosol burden. Biogenic organic material is both directly emitted into the atmosphere and produced by VOCs. All biogenic VOC emissions are highly sensitive to changes in temperature, and are also highly sensitive to climate-induced changes in plant species composition and biomass distributions. Biogenic emissions rates are predicted to increase, on average across world regions, by 10% per 1°C increase in surface temperature (Denman et al., 2007; Guenther et al. 1993). The response of biogenic secondary organic carbon aerosol production to a temperature change, however, could be considerably lower than the response of biogenic VOC emissions since aerosol yields can decrease with increasing temperature (Denman et al., 2007).

Particulate matter emissions from forest fires can contribute to acute and chronic illnesses of the respiratory system, particularly in children, including pneumonia, upper respiratory diseases, asthma and chronic obstructive pulmonary diseases (WHO, 2002; Bowman and Johnston, 2005; Moore et al., 2006; Confalonieri et al., 2007). The IPCC (Field et al., 2007) reported with very high confidence that in North America disturbances like wildfire are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons. Pollutants from forest fires can affect air quality for thousands of kilometers (Confalonieri et al., 2007). Westerling et al. (2006; as referenced in IPCC (Field et al., 2007)) found that, in the last three decades, the wildfire season in the western U.S. has increased by 78 days, and burn durations of large fires have increased from 7.5 to 37.1 days, in response to a spring-summer warming of 0.87°C. Earlier spring snowmelt has led to longer growing seasons and drought, especially at

higher elevations, where the increase in wildfire activity has been greatest (Westerling et al., 2006). Analysis by the State of California suggests that large wildfires could become up to 55% more frequent in some areas toward the end of the century due to continued global warming (California Climate Change Center, 2006).

Particulate matter chemistry is affected by changes in temperature brought about by climate change as follows. Temperature is one of the most important meteorological variables influencing air quality in urban atmospheres because it directly affects gas and heterogeneous chemical reaction rates and gas-to-particle partitioning. The net effect that increased temperature has on airborne particle concentrations is a balance between increased production rates for secondary particulate matter (increases particulate concentrations) and increased equilibrium vapor pressures for semi-volatile particulate compounds (decreases particulate concentrations). Increased temperatures may either increase or decrease the concentration of semi-volatile secondary reaction products such as ammonium nitrate depending on ambient conditions.

The IPCC (Denman et al., 2007) notes that there has been less work on the sensitivity of aerosols to meteorological conditions and cites regional model simulations by Aw and Kleeman (2003). The regional model simulations for Southern California on September 25, 1996 projected decreases in 24-hour average PM_{2.5} concentrations with increasing temperatures for inland portions of the South Coast air basin, and projected increases for coastal regions. Increased temperatures may either increase or decrease the concentration of semi-volatile secondary reaction products such as ammonium nitrate depending on ambient conditions. Regions with relatively hot initial temperatures (>290 K) will likely experience a reduction in particulate ammonium nitrate concentrations as temperature increases, while regions with relatively cool initial temperatures (<290 K) may experience minor reductions or even small increases in particulate ammonium nitrate concentrations as temperature increases. The net effect that increased temperature has on airborne particle concentrations is a balance between increased production rates for secondary PM (increases particulate concentrations) and increased equilibrium vapor pressures for semi-volatile particulate compounds (decreases particulate concentrations).

The transport and removal of PM is highly sensitive to winds and precipitation. Removal of PM from the atmosphere occurs mainly by wet deposition (NAS, 2005). Sulfate lifetime, for example, is estimated to be reduced from 4.7 days to 4.0 days as a result of increased wet deposition (Liao and Seinfeld, 2006). Precipitation also affects soil moisture, with impacts on dust source strength and on stomatal opening/closure of plant leaves, hence affecting biogenic emissions (Denman et al., 2007). Precipitation has generally increased over land north of 30°N over the period 1900 to 2005 and it has become significantly wetter in eastern parts of North America (Trenberth et al., 2007). parameterizations of wet deposition are highly uncertain and not fully realistic in their coupling to the hydrological cycle (NAS, 2005). For models to simulate accurately the seasonally varying pattern of precipitation, they must correctly simulate a number of processes (e.g., evapotranspiration, condensation, transport) that are difficult to evaluate at a global scale (Randall et al., 2007). In 1997, EPA demonstrated that visibility impairment is an important effect on public welfare and that visibility impairment is experienced (though not necessarily attributed to climate change) throughout the U.S., in multi-state regions, urban areas, and remote Federal Class I areas⁵⁴. Visibility impairment depends strongly on ambient relative humidity (NARSTO, 2004). Although surface specific humidity globally has generally increased after 1976 in close association with higher temperatures over both land and ocean, observations suggest that relative humidity has remained about the same overall, from the surface throughout the

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⁵⁴ The Clean Air Act defines mandatory Federal Class I areas as certain national parks (over 6,000 acres), wilderness areas (over 5,000 acres), national memorial parks (over 5,000 acres), and international parks that were in existence as of August 7, 1977.

troposphere (Trenberth et al., 2007). Nevertheless, increases in PM due to increases in wildfires induced by climate change might increase visibility impairment.

Section 9

2 3

Food Production and Agriculture

Food production and the agricultural sector within the U.S. are sensitive to short-term climate variability and long-term climate change. This section addresses how observed and projected climate change may affect U.S. food production and agriculture. Food production and agriculture here include crop yields and production, livestock production (e.g., milk and meat), freshwater fisheries, and key climate-sensitive issues for this sector including drought risk and pests and weeds.

In addition to changes in average temperatures and precipitation patterns, this section also addresses how U.S. food production and agriculture may be affected directly by elevated CO₂ levels, as well as the frequency and severity of extreme events, such as droughts and storms. Climate change-induced effects on tropospheric ozone levels and their impacts on agriculture are discussed in Section 8 on Air Quality.

Vulnerability of the U.S. agricultural sector to climate change is a function of many interacting factors including pre-existing climatic and soil conditions, changes in pest competition, water availability, and the sector's capacity to cope and adapt through management practices, seed and cultivar technology, and changes in economic competition among regions.

The IPCC (2007b) made the following conclusion about food production and agriculture for North America:

Moderate climate change in the early decades of the century is projected to increase aggregate yields of rainfed agriculture by 5-20%, but with important variability among regions. Major challenges are projected for crops that are near the warm end of their suitable range or depend on highly utilized water resources [high confidence]. 55

The CCSP (2008a) report addressing agriculture made the following general conclusions for the U.S.:

• With increased CO₂ and temperature, the life cycle of grain and oilseed crops will likely progress more rapidly. But, as temperature rises, these crops will increasingly begin to experience failure, especially if climate variability increases and precipitation lessens or becomes more variable.

• The marketable yield of many horticultural crops – e.g., tomatoes, onions, fruits – is very likely to be more sensitive to climate change than grain and oilseed crops.

• Climate change is likely to lead to a northern migration of weeds.

 • Disease pressure on crops and domestic animals will likely increase with earlier springs and warmer winters, which will allow proliferation and higher survival rates of pathogens and parasites. Regional variation in warming and changes in rainfall will also affect spatial and temporal distribution of disease.

• Projected increases in temperature and a lengthening of the growing season will likely extend forage production into late fall and early spring, thereby decreasing need for winter season forage reserves.

⁵⁵ According to IPCC terminology, "high confidence" conveys an 8 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

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Climate change-induced shifts in plant species are already underway in rangelands.

Higher temperatures will very likely reduce livestock production during the summer season, but these losses will very likely be partially offset by warmer temperatures during the winter season.

9(a) **Crop yields and productivity**

The IPCC Fourth Assessment conclusion that North American rain-fed agriculture is projected to experience net benefits with moderate climate change, with significant regional variation, generally confirms the previous conclusion from the IPCC Third Assessment Report (2001). ⁵⁶ Moderate climate change for temperate regions such as the U.S. is described as local increases in temperature of 1-3°C (~2-5°F), which may occur within the next few decades or past mid-century depending on scenario (see Section 6 for temperature projections). Increased average warming leads to an extended growing season, especially for northern regions of the U.S. Further warming, however, is projected to have increasingly negative impacts in all regions (meaning both temperate, including the U.S., and tropical regions of the world) (Easterling et al. 2007).

Observational evidence shows that, over the last century, aggregate yields of major U.S. crops have been increasing (USDA, 2007; Troyer, 2004 as referenced in Field et al., 2007), with significant regional and temporal variation. Multiple factors contribute to these long term trends, including seed technology, use of fertilizers, management practices, and climate change. Weather events are a major factor in annual crop yield variation. The IPCC (Field et al., 2007 and references therein) reviewed a number of studies showing the effects of weather and climate variability on U.S. crop yields:

- Excessive soil moisture reduced the value of the U.S. corn crop by an average of 3% or US\$600 million/yr between 1951-1998 (Rosenzweig et al., 2002);
- In California, warmer nights have enhanced the production of high-quality wine grapes, but additional warming may not result in similar increases as wine grapes may already be near climate thresholds:
- For twelve major crops in California, climate fluctuations over the last 20 years have not had large effects on yield, though they have been a positive factor for oranges and walnuts but negative for avocados and cotton.

For projected climate change effects, the IPCC summary conclusion of net beneficial effects in the early decades in the U.S., with significant regional variation, is supported by a number of recent assessments for most major crops. The variable future climate change effects among regions and crops have also been identified. For example, the south-eastern U.S. may be more vulnerable to increases in average temperature than more northern regions due to pre-existing temperatures that are already relatively high. Likewise, certain crops that are currently near climate thresholds (e.g., wine grapes in California) are likely to experience decreases in yields, quality, or both, even under moderate climate change scenarios (Field et al., 2007).

Changes in precipitation patterns will play a large role in determining the net impacts of climate change at the national and sub-national scales, where uncertainties about precipitation changes remain very large. The IPCC (Field et al., 2007) reviewed integrated assessment modeling studies exploring the interacting

⁵⁶ The North America chapter from the IPCC Third Assessment Report (Cohen et al. 2007) concluded: "Food production is projected to benefit from a warmer climate, but there probably will be strong regional effects, with some areas in North America suffering significant loss of comparative advantage to other regions (high confidence)."

impacts of climate and economic factors on agriculture, water resources, and biome boundaries in the U.S. and concluded that scenarios with decreased precipitation create important challenges, restricting the availability of water for irrigation and at the same time increasing water demand for irrigated agriculture, as well as urban and ecological uses. The critical importance of specific agro-climatic events, such as last frost, also introduces uncertainty in future projections (Field et al., 2007).

There is still debate and uncertainty about the sensitivity of crop yields in the U.S. and other world regions to the direct effects of elevated CO₂ levels. The IPCC (Easterling et al., 2007) concluded that elevated CO₂ levels are expected to contribute to small beneficial impacts on crop yields. The IPCC confirmed the general conclusions from its previous Third Assessment Report in 2001. Experimental research on crop responses to elevated CO₂ through the FACE (Free Air CO₂ Enrichment)⁵⁷ experiments indicate that, at ambient CO₂ concentrations of 550 ppm (approximately double the concentration from pre-industrial times), crop yields increase under unstressed conditions by 10-25% for C3 crops, and by 0-10% for C4 crops (medium confidence)⁵⁸. Crop model simulations under elevated CO₂ are consistent with these ranges (high confidence) (Easterling et al., 2007). High temperatures, water and nutrient availability, and ozone exposure, however, can significantly limit the direct stimulatory CO₂ response (see also Section 8 on Air Quality). The CCSP (2008a) report concluded that the benefits of CO₂ rise over the next 30 years will mostly offset the negative effects of temperature for most C3 crops except rice and bean, while the C4 crop yields will be reduced by rising temperatures because they have little response to the CO₂ rise.

9(b) Irrigation requirements

The impacts of climate change on irrigation water requirements may be large (Easterling et al., 2007). The IPCC considered this to be a new, robust finding since the Third Assessment Report in 2001. The increase in irrigation demand due to climate change is expected in the majority of world regions including the U.S. due to decreased rainfall in certain regions and/or increased evaporation arising from increased temperatures. Longer growing seasons may contribute to the increased irrigation demands as well. In modeling studies of future climate change, additional irrigation is often assumed in order to counterbalance the potential adverse yield effects of significant temperature increases (Easterling et al., 2007).

9(c) Climate variability and extreme events

The projected impacts of climate change often consider changes in *average* temperature and precipitation patterns alone, while not reflecting the potential for altered variability in events such as droughts and floods. The potential for these events to change in frequency and magnitude introduces a key uncertainty regarding IPCC's general conclusion that U.S. agriculture, in aggregate, is expected to benefit under modest climate change. On this issue, the IPCC (Easterling et al. 2007) drew the following conclusion: "Recent studies indicate that climate change scenarios that include increased frequency of heat stress, droughts and flooding events reduce crop yields and livestock productivity beyond the impacts due to changes in mean variables alone, creating the possibility for surprises. Climate variability and change also modify the risks of fires, and pest and pathogen outbreaks, with negative consequences for food, fiber and forestry (high confidence)." The adverse effects on crop yields due to droughts and other extreme events may offset the beneficial direct effects of elevated CO₂, moderate temperature increases over the near term, and longer growing seasons.

⁵⁷ http://www.bnl.gov/face/

⁵⁸ C3 and C4 refer to different carbon fixation pathways in plants during photosynthesis. C3 is the most common pathway, and C3 crops (e.g., wheat, soybeans and rice) are more responsive than C4 crops such as maize.

Drought events are already a frequent occurrence, especially in the western U.S. Vulnerability to extended drought is, according to IPCC (Field et al., 2007), increasing across North America as population growth and economic development increase demands from agricultural, municipal, and industrial uses, resulting in frequent over-allocation of water resources. Though droughts occur more frequently and intensely in the western part of the U.S., the east is not immune from droughts and attendant reductions in water supply, changes in water quality and ecosystem function, and challenges in allocation (Field et al., 2007).

Average annual precipitation is projected to decrease in the southwestern U.S. but increase over the rest of North America (Christensen et al., 2007). Some studies project widespread increases in extreme precipitation (Christensen et al., 2007), with greater risks of not only flooding from intense precipitation, but also droughts from greater temporal variability in precipitation.

9(d) Pests and weeds

Pests and weeds can reduce crop yields, cause economic losses to farmers, and require management control options. How climate change (elevated CO₂, increased temperatures, altered precipitation patterns, and changes in the frequency and intensity of extreme events) may affect the prevalence of pests and weeds is an issue of concern for food production and the agricultural sector. Recent warming trends in the U.S. have led to earlier insect spring activity and proliferation of some species (Easterling, et al., 2007). Weeds generally respond more positively to increasing CO₂ than most cash crops, particularly C3 invasive weeds; and while there are many weed species that have the C4 photosynthetic pathway and therefore show a smaller response to atmospheric CO₂ relative to C3 crops, in most agronomic situations, crops are in competition with both C3 and C4 weeds (CCSP, 2008a). The IPCC (Easterling et al., 2007) concluded, with high confidence, that climate variability and change modify the risks of fires, and pest and pathogen outbreaks, with negative consequences for food, fiber and forestry across all world regions.

Most studies, however, continue to investigate pest damage as a separate function of either elevated ambient CO₂ concentrations or temperature. Pests and weeds are additional factors that, for example, are often omitted when projecting the direct stimulatory effect of elevated CO₂ on crop yields. Research on the combined effects of elevated CO₂ and climate change on pests, weeds and disease is still insufficient for U.S. and world agriculture (Easterling et al., 2007).

9(e) Livestock

Climate change has the potential to influence livestock productivity in a number of ways. Elevated CO₂ concentrations can affect forage quality; thermal stress can directly affect the health of livestock animals; an increase in the frequency or magnitude of extreme events can lead to livestock loss; and climate change may affect the spread of animal diseases. The IPCC has generated a number of new conclusions in this area compared to the Third Assessment Report in 2001. These conclusions, applicable to U.S. and other livestock producing regions, include (from Easterling et al., 2007 unless noted otherwise):

• Changes in forage quality: Elevated CO₂ can increase the carbon to nitrogen ratio in forages and thus reduce the nutritional value of those grasses, which in turn affects animal weight and performance. Under elevated CO₂, a decrease of C4 grasses and an increase of C3 grasses (depending upon the plant species that remain) may occur which could potentially reduce or alter the nutritional quality of the forage grasses available to grazing livestock; however the exact effects on both types of grasses and their nutritional quality still needs to be determined.

• Thermal stress reduces productivity, conception rates and is potentially life threatening to livestock. According to one sensitivity study reviewed in IPCC (Frank et al., 2001), the U.S. estimated

percentage decrease in swine, beef and dairy milk production in 2050 averaged 1.2%, 2.0%, and 2.2%, respectively, using one climate model and 0.9%, 0.7%, and 2.1%, respectively, using a different climate model. However, reduced livestock production due to higher temperatures in the summer may be offset due to higher temperatures during the winter (CCSP, 2008a).

• Increased climate variability (including extremes in both heat and cold) and droughts may lead to livestock loss. The impact on animal productivity due to increased variability in weather patterns will likely be far greater than effects associated with the average change in climatic conditions.

9(f) Freshwater and marine fisheries

Freshwater fisheries are sensitive to changes in temperature and water supply, which affect flows of rivers and streams, as well as lake levels. Climate change can interact with other factors that affect the health of fish and productivity of fisheries (e.g., habitat loss, land-use change).

The IPCC (Field et al., 2007 and references therein) reviewed a number of North American studies showing how freshwater fish are sensitive to, or are being affected by, observed changes in climate:

- Cold- and cool-water fisheries, especially salmonids, have been declining as warmer/drier conditions reduce their habitat. The sea-run salmon stocks are in steep decline throughout much of North America:
- Pacific salmon have been appearing in Arctic rivers;⁵⁹
- Salmonid species have been affected by warming in U.S. streams;
- Success of adult spawning and survival of fry brook trout is closely linked to cold groundwater seeps, which provide preferred temperature refuges for lake-dwelling populations. Rates of fish egg development and mortality increase with temperature rise within species-specific tolerance ranges.

Regarding the impacts of future climate change, IPCC concluded, with high confidence for North America, that cold-water fisheries will likely be negatively affected; warm-water fisheries will generally benefit; and the results for cool-water fisheries will be mixed, with gains in the northern and losses in the southern portions of ranges (Field et al., 2007). A number of specific impacts by fish species and region in North America are projected (Field et al., 2007 and references therein):

- Salmonids, which prefer cold water, are likely to experience the most negative impacts;
- Arctic freshwaters will likely be most affected, as they will experience the greatest warming;
- Many warm-water and cool-water species will shift their ranges northward or to higher altitudes;
- In the continental U.S., cold-water species will likely disappear from all but the deeper lakes, coolwater species will be lost mainly from shallow lakes, and warm water species will thrive except in the far south, where temperatures in shallow lakes will exceed survival thresholds.

Climate variability and change can also impact fisheries in coastal and estuarine waters, although nonclimatic factors, such as overfishing and habitat loss and degradation, are already responsible for reducing fish stocks (Nichols et al., 2007). Coral reefs, for example, are vulnerable to a range of stresses and for many reefs, thermal stress thresholds will be crossed, resulting in bleaching, with severe adverse consequences for reef-based fisheries (Nichols et al., 2007). Increased storm intensity, temperature and salt water intrusion in coastal water bodies can also adversely impact coastal fisheries production.

⁵⁹ Arctic includes large regions of Alaska, and the Alaskan indigenous population makes up largest indigenous population of the Arctic (see ACIA, 2004).

Section 10

Forestry

This section addresses how climate change may affect forestry, including timber yields, wildfires and drought risk, forest composition, and pests in the U.S. For North America, the IPCC (Field et al., 2007) concluded:

• Overall forest growth in North America will likely increase modestly (10-20%) as a result of extended growing seasons and elevated CO₂ over the next century, but with important spatial and temporal variation (medium confidence). 60

• Disturbances like wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons (very high confidence). Although recent climate trends have increased vegetation growth, continuing increases in disturbances are likely to limit carbon storage, facilitate invasive species, and disrupt ecosystem services. Over the 21st century, pressure for species to shift north and to higher elevations will fundamentally rearrange North American ecosystems. Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections will alter ecosystem structure, function, and services.

The CCSP (2008a) report addressing forestry and land resources made the following general conclusions for the U.S.:

• Climate change has very likely increased the size and number of forest fires, insect outbreaks, and tree mortality in the interior West, the Southwest, and Alaska, and will continue to do so.

Rising CO₂ will very likely increase photosynthesis for forests, but this increase will likely only
enhance wood production in young forests on fertile soils.

• The combined effects of rising temperatures and CO₂, nitrogen deposition, ozone, and forest disturbance on soil processes and soil carbon storage remains unclear.

10(a) Forest Productivity

 Forestry productivity is known to be sensitive to changes in climate variables (e.g. temperature, radiation, precipitation, water vapor pressure in the air, and wind speed), as these affect a number of physical, chemical, and biological processes in forest systems (Easterling, et al., 2007). However, as noted in a CCSP report addressing the forest sector (Ryan et al., 2008), it is difficult to separate the role of climate from other potentially influencing factors, particularly because these interactions vary by location.

For the U.S. as a whole, forest growth and productivity have been observed to change, in part due to observed climate change. Nitrogen deposition and warmer temperatures have very likely increased forest growth where water is not limiting (CCSP, 2008a). The IPCC (Field et al., 2007 and references therein) outlines a number of studies demonstrating the observed connection between changes in U.S. forest growth and changes in climate variables:

⁶⁰ According to IPCC terminology, "medium confidence" conveys a 5 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

- Forest growth appears to be slowly accelerating (less than 1% per decade) in regions where tree growth has historically been limited by low temperatures and short growing seasons;
- The length of the vegetation growing season has increased an average of 2 days per decade since 1950 in the conterminous U.S., with most of the increase resulting from earlier spring warming;
- Growth is slowing in areas subject to drought;

- On dry south-facing slopes in Alaska, growth of white spruce has decreased over the last 90 years, due to increased drought stress;
- In semi-arid forests of the south-western U.S., growth rates have decreased since 1895, correlated with drought from warming temperatures;
- Mountain forests are increasingly encroached upon from adjacent lowlands, while simultaneously losing high altitude habitats due to warming (Fischlin et al., 2007).
- In Colorado, aspen have advanced into the more cold-tolerant spruce-fir forests over the past 100 years;
 A combination of warmer temperatures and insect infestations has resulted in economically
 - A combination of warmer temperatures and insect infestations has resulted in economically significant losses of forest resource base to spruce bark beetle in Alaska.

Forest productivity gains may result through: (i) the direct stimulatory CO₂ fertilization effect (although the magnitude of this effect remains uncertain over the long term and can be curtailed by other changing factors); (ii) warming in cold climates, given concomitant precipitation increases to compensate for possibly increasing water vapor pressure deficits; and (iii) precipitation increases under water limited conditions (Fischlin et al., 2007).

New studies suggest that direct CO₂ effects on tree growth may be lower than previously assumed. Additionally, the initial increase in growth increments may be limited by competition, disturbance, air pollutants (primarily tropospheric ozone), nutrient limitations, ecological processes, and other factors, and the response is site- and species-specific (Easterling et al., 2007). Similarly, a CCSP (2008a) report stated that, where nutrients are not limiting, rising CO₂ increases photosynthesis and wood production, but that on infertile soils the extra carbon from increased photosynthesis will be quickly respired.

Productivity gains in one area can occur simultaneously with productivity losses in other areas. For a widespread species like lodgepole pine, a 3°C temperature increase would increase growth in the northern part of its range, decrease growth in the middle, and decimate southern forests (Field et al., 2007). Climate change is expected to increase California timber production by the 2020s because of stimulated growth in the standing forest. In the long run (up to 2100), these productivity gains were offset by reductions in productive area for softwoods growth. Risks of losses from Southern pine beetle likely depend on the seasonality of warming, with winter and spring warming leading to the greatest damage (Easterling et al., 2007 and references therein).

According to studies reviewed by IPCC (Field et al., 2007), the effects of climate change, in the absence of dramatic increases in disturbance, on the potential for commercial harvest in the 2040s ranged from mixed for a low emissions scenario to positive for a high emissions scenario (see Perez-Garcia et al., 2002). The tendency for North American producers to suffer losses increases if climate change is accompanied by increased disturbance, with simulated losses averaging US\$1-2 billion/year, over the 21st century (Sohngen and Sedjo, 2005).

U.S. forestry, in addition to experiencing direct climate change effects, may be indirectly affected by changing forest productivity in different regions of the world. Sohngen and Sedjo (2005) show two climate change scenarios where North American forests undergo more dieback in general than forests in other regions of the world, and where certain North American forest yields increase but less so compared to other regions. The implication is that forests in other parts of the world (including tropical forests with

shorter rotations) could have a competitive advantage within the global forestry sector under a changing climate.

Climate change will also substantially impact other non-timber goods and services, such as seeds, nuts, hunting, resins, plants used in pharmaceutical and botanical medicine, and in the cosmetics industry; these impacts will vary significantly across world regions (Easterling et al., 2007).

10(b) Wildfire and Drought Risk

While in some cases a changing climate may have positive impacts on the productivity of forest systems, changes in disturbance patterns are expected to have a substantial impact on overall gains or losses. More prevalent forest fire disturbances have recently been observed in the U.S. and other world regions (Fischlin, et al., 2007). Wildfires and droughts, among other extreme events (e.g., hurricanes) that can cause forest damage, pose the largest threats over time to forest ecosystems. The frequency and severity of wildfires and droughts are expected to be altered by climate change, which can also induce stress on trees that indirectly exacerbate disturbances. General climate warming encourages wildfires by extending the summer period that dries fuels, promoting easier ignition and faster spread (Field et al., 2007).

The IPCC (Field et al., 2007 and references therein) noted a number of observed changes to U.S. wildfire size and frequency, often associating these changes with changes in average temperatures:

- Since 1980, an average of about 22,000 km²/year (13,700 mi²/year) has burned in wildfires, almost twice the 1920-1980 average of about 13,000 km²/year (8,080 mi²/year);
- The forested area burned in the western U.S. from 1987-2003 is 6.7 times the area burned from 1970-1986:
- Human vulnerability to wildfires has increased, with a rising population in the wildland-urban interface:
- In the last three decades, the wildfire season in the western U.S. has increased by 78 days, and burn durations of fires greater than 1,000 ha (2,470 acres) have increased from 7.5 to 37.1 days, in response to a spring/summer warming of 0.87°C (1.4°F);
- Earlier spring snowmelt has led to longer growing seasons and drought, especially at higher elevations, where the increase in wildfire activity has been greatest;
- In the south-western U.S., fire activity is correlated with higher Palmer Drought Severity Indices. 61

Though fires and extreme events are not well represented in models, current modeling studies suggest that increased temperatures and longer growing seasons will elevate fire risk in connection with increased aridity. Some research identifies the possibility of a 10% increase in the seasonal severity of fire hazard over much of the U.S. under climate change (Easterling, et al., 2007). For Arctic regions, forest fires are expected to increase in frequency and intensity (ACIA, 2004). In California, the risk of increased wildfires as a result of climate change has been identified as a significant issue (California Energy Commission, 2006).

10(c) Forest Composition

Climate change and associated changes in disturbance regimes will cause shifts in the distributions of tree species and alter forest species composition. With warming, forests will extend further north and to higher elevations. Over currently dry regions, increased precipitation may allow forests to displace

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⁶¹ The Palmer Drought Severity Index is used by NOAA and uses a formula that includes temperature and rainfall to determine dryness. It is most effective in determining long-term drought.

grasslands and savannas. Changes in forest composition in turn can alter the frequencies, intensities, and impacts of disturbances such as fire, insect outbreaks, and disease.

In Alaska and neighboring Arctic regions, there is strong evidence of recent vegetation composition change, as outlined by the IPCC (Anisimov et al., 2007 and references therein 62):

- Aerial photographs show increased shrub abundance in 70% of 200 locations;
- Along the Arctic to sub-Arctic boundary, the tree-line has moved about 6 mi (10 km) northwards and 2% of Alaskan tundra on the Seward Peninsula has been displaced by forest in the past 50 years;
- The pattern of northward and upward tree-line advances is comparable with earlier Holocene changes;
- Analyses of satellite images indicate that the length of growing season is increasing by 3 days per decade in Alaska.

Likely rates of migration northward and to higher elevations are uncertain and depend not only on climate change but also on future land-use patterns and habitat fragmentation, which can impede species migration. Bioclimatic modeling based on outputs from five general circulation models suggests that, over the next century, tree species richness will decrease in most parts of the conterminous U.S., even though long-term trends (millennia) ultimately favor increased richness in some locations (Field, et al., 2007). The Arctic Climate Impact Assessment (2004) also concluded that vegetation zones are projected to migrate northward, with forests encroaching on tundra and tundra encroaching on polar deserts. Limitations in amount and quality of soils are likely to hinder these poleward shifts.

10(d) Insects and Diseases

Insects and diseases are a natural part of forested ecosystems and outbreaks often have complex causes. The effects of insects and diseases can vary from defoliation and retarded growth, to timber damage, to massive forest diebacks. Insect life cycles can be a factor in pest outbreaks; and insect lifecycles are sensitive to climate change. Many northern insects have a two-year life-cycle, and warmer winter temperatures allow a larger fraction of overwintering larvae to survive. Recently, spruce budworm in Alaska has completed its life cycle in one year, rather than the previously observed duration of two years (Field et al., 2007). Recent warming trends in the U.S. have led to earlier spring activity of insects and proliferation of some species, such as the mountain pine beetle (Easterling et al., 2007). During the 1990s, Alaska's Kenai Peninsula experienced an outbreak of spruce bark beetle over 16,000 km² with 10-20% tree mortality. Also following recent warming in Alaska, spruce budworm has reproduced farther north reaching problematic numbers (Anisimov et al., 2007).

Climate change may indirectly affect insect outbreaks by affecting the overall health and productivity of trees. For example, susceptibility of trees to insects is increased when multi-year droughts degrade the trees' ability to generate defensive chemicals (Field, et al., 2007). Warmer temperatures have already enhanced the opportunities for insect spread across the landscape in the U.S. and other world regions (Easterling et al., 2007).

The IPCC (Easterling et al., 2007) stated that modeling of future climate change impacts on insect and pathogen outbreaks remains limited. Nevertheless, the IPCC (Field et al., 2007) states with high confidence that, across North America, impacts of climate change on commercial forestry potential are likely to be sensitive to changes in disturbances from insects and diseases, as well as wildfires. Climate change can shift the current boundaries of insects and pathogens and modify tree physiology and tree

⁶² The Anisimov et al. citation refers to Chapter 15, "Polar Regions (Arctic and Antarctic)" in IPCC's 2007 Fourth Assessment Report, Working Group II.

defense. An increase in climate extremes may also promote plant disease and pest outbreaks (Easterling, et al., 2007).

Section 11

Water Resources

This section covers climate change effects on U.S. water supply, water quality, extreme events affecting water resources, and water uses. Information about observed trends as well as projected impacts is provided.

For North America, IPCC concluded:

• Climate change will constrain North America's over-allocated water resources, increasing competition among agricultural, municipal, industrial, and ecological uses (very high confidence)⁶³ (Field et al., 2007). Rising temperatures will diminish snowpack and increase evaporation, affecting seasonal availability of water. Higher demand from economic development, agriculture and population growth will further limit surface and groundwater availability. In the Great Lakes and major river systems, lower levels are likely to exacerbate challenges relating to water quality, navigation, recreation, hydropower generation, water transfers, and bi-national relationships.

11(a) Water Supply and Snowpack

Surface Water and Snowpack

The semi-humid conditions of the eastern U.S. yield to drier conditions to the west, with increasing dryness eventually interrupted by the Rocky Mountains. The driest climates, however, exist in the Intermountain West and Southwest, which give way as one proceeds west and north to more humid conditions on the upslope areas of the Cascade and coastal mountain ranges, especially in the Pacific Northwest (Lettenmaier et al., 2008).

IPCC reviewed a number of studies showing trends in U.S. precipitation patterns, surface water supply, and snowpack, and how climate change may be contributing to some of these trends (Field et al., 2007):

Annual precipitation has increased throughout most of North America.

 • Streamflow in the eastern U.S. has increased 25% in the last 60 years, but has decreased by about 2% per decade in the central Rocky Mountain region over the last century.

 • Since 1950, stream discharge in both the Colorado and Columbia river basins has decreased.

• In regions with winter snow, warming has shifted the magnitude and timing of hydrologic events. The fraction of annual precipitation falling as rain (rather than snow) increased at 74% of the weather stations studied in the western mountains of the U.S. from 1949-2004.

 • Spring and summer snow cover has also decreased in the U.S. West. April snow water equivalents have declined 15-30% since 1950 in the western mountains of North America, particularly at lower elevations, due primarily to warming temperatures rather than changes in precipitation (See Figure 14.1).

• Break-up of river and lake ice across North America advanced by 0.2 – 12.9 days over the last 100 years.

⁶³ According to IPCC terminology, "very high confidence" conveys a 9 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

In the Arctic, precipitation has increased by about 8% on average over the past century. Much of the increase has fallen as rain, with the largest increases occurring in autumn and winter. Later freeze-up and earlier break-up of river and lake ice have combined to reduce the ice season by one to three weeks in some areas. Glaciers throughout North America are melting, and the particularly rapid retreat of Alaskan glaciers represents about half of the estimated loss of glacial mass worldwide (ACIA, 2004). Permafrost plays a large role in the hydrology of lakes and ponds. The spatial pattern of lake disappearance strongly suggests that permafrost thawing is driving the changes. These changes to Arctic precipitation, ice extent, and glacial abundance will affect key regional bio-physical systems, act as climatic feedbacks (primarily by changing surface albedo), and have socio-economic impacts (high confidence) (Anisimov et al., 2007). The vulnerability of freshwater resources in the U.S. to climate change varies from region to region. In regions including the Colorado River, Columbia River, and Ogallala Aquifer, surface and/or groundwater resources are intensively used and subject to competition from agricultural, municipal, industrial, and ecological needs. This increases the potential vulnerability to future changes in timing and availability of water (Field et al., 2007).

Projections for the western mountains of the U.S. suggest that warming, and changes in the form, timing, and amount of precipitation will very likely lead to earlier melting and significant reductions in snowpack by the middle of the 21st century (IPCC: high confidence). In mountainous snowmelt-dominated watersheds, projections suggest advances in the timing of snowmelt runoff, increases in winter and early spring flows (raising flooding potential), and substantially decreased summer flows. Heavily-utilized water systems of the western U.S. that rely on capturing snowmelt runoff, such as the Columbia River system, will be especially vulnerable (Field et al., 2007). Reduced snowpack has been identified as a major concern for the State of California (California Energy Commission, 2006).

Globally, current water management practices are very likely to be inadequate to reduce the negative impacts of climate change on water supply reliability, flood risk, and aquatic ecosystems (very high confidence) (Kundzewicz et al., 2007⁶⁴). Less reliable supplies of water are likely to create challenges for managing urban water systems as well as for industries that depend on large volumes of water. U.S. water managers currently anticipate local, regional, or state-wide water shortages over the next ten years. Threats to reliable supply are complicated by high population growth rates in western states where many resources are at or approaching full utilization. Potential increases in heavy precipitation, with expanding impervious surfaces, could increase urban flood risks and create additional design challenges and costs for stormwater management (Field et al., 2007). The IPCC (Field et al., 2007 and references therein) reviewed several regional-level studies on climate change impacts to U.S. water management which showed:

- In the Great Lakes St. Lawrence Basin, many, but not all, assessments project lower net basin supplies and lake water levels. Lower water levels are likely to influence many sectors, with multiple, interacting impacts (IPCC: high confidence). Atmosphere-lake interactions contribute to the uncertainty in assessing these impacts though.
- Urban water supply systems in North America often draw water from considerable distances, so climate impacts need not be local to affect cities. By the 2020s, 41% of the water supply to southern California is likely to be vulnerable due to snowpack loss in the Sierra Nevadas and Colorado River basin.
- The New York area will likely experience greater water supply variability. New York City's system can likely adapt to future changes, but the region's smaller systems may be vulnerable, leading to a need for enhanced regional water distribution plans.

⁶⁴ The Kundzewicz et al. citation refers to Chapter 3, "Freshwater Resources and their Management" in IPCC's 2007 Fourth Assessment Report, Working Group II.

In the Arctic, river discharge to the ocean has increased during the past few decades, and peak flows in the spring are occurring earlier. These changes are projected to accelerate with future climate change. Snow cover extent in Alaska is projected to decrease by 10-20% by the 2070s, with greatest declines in spring (ACIA, 2004 and reference therein).

The IPCC concluded with high confidence that under most climate change scenarios, water resources in small islands around the globe are likely to be seriously compromised (Mimura et al., 2007). Most small islands have a limited water supply, and water resources in these islands are especially vulnerable to future changes and distribution of rainfall. Reduced rainfall typically leads to decreased surface water supply and slower recharge rates of the freshwater lens⁶⁵, which can result in prolonged drought impacts. Many islands in the Caribbean (which include U.S. territories of Puerto Rico and U.S. Virgin Islands) are likely to experience increased water stress as a result of climate change. Under all SRES scenarios, reduced rainfall in summer is projected for the Caribbean, making it unlikely that the demand for water resources will be met. Increased rainfall in winter is unlikely to compensate for these water deficits due to lack of storage capacity (Mimura et al., 2007⁶⁶).

Groundwater

Groundwater systems generally respond more slowly to climate change than surface water systems. Limited data on existing supplies of groundwater makes it difficult to understand and measure climate effects. In general, groundwater levels correlate most strongly with precipitation, but temperature becomes more important for shallow aquifers, especially during warm periods. In semi-arid and arid areas, groundwater resources are particularly vulnerable because precipitation and streamflow are concentrated over a few months, year-to-year variability is high, and deep groundwater wells or reservoirs generally do not exist (Kundzewicz et al., 2007).

With climate change, availability of groundwater is likely to be influenced by changes in withdrawals (reflecting development, demand, and availability of other sources) and recharge (determined by temperature, timing, and amount of precipitation, and surface water interactions) (medium confidence). In general, simulated aquifer levels respond to changes in temperature, precipitation, and the level of withdrawal. According to IPCC, base flows were found to decrease in scenarios that are drier or have higher pumping rates, and increase in wetter scenarios on average across world regions (Kundzewicz et al., 2007).

Projections suggest that efforts to offset declining surface water availability by increasing groundwater withdrawals will be hampered by decreases in groundwater recharge in some water-stressed regions, such as the southwest US. Vulnerability in these areas is also often exacerbated by the rapid increase of population and water demand (high confidence) (Kundzewicz et al., 2007). Projections for the Ogallala aquifer region suggest that natural groundwater recharge decreases more than 20% in all simulations with different climate models and future warming scenarios of 2.5°C or greater (Field et al., 2007 and reference therein).

⁶⁵ Freshwater lens is defined as a relatively thin layer of freshwater within island aquifer systems that floats on an underlying mass of denser seawater. Numerous factors control the shape and thickness of the lens, including the rate of recharge from precipitation, island geometry, and geologic features such as the permeability of soil layers. ⁶⁶ Mimura et al., 2007 refers to Chapter 16, "Small Islands" in IPCC's 2007 Fourth Assessment Report, Working

Group II.

In addition, sea level rise will extend areas of salinization of groundwater and estuaries, resulting in a decrease in freshwater availability for humans and ecosystems in coastal areas. For a discussion of these impacts, please see Section 12.

11(b) Water Quality

The IPCC concluded with high confidence that higher water temperatures, increased precipitation intensity, and longer periods of low flows exacerbate many forms of water pollution and can impact ecosystems, human health, and water system reliability and operating costs. A CCSP (2008a) report also acknowledges that water quality is sensitive to both increased water temperatures and changes in precipitation; however, most water quality changes observed so far in the U.S. are likely attributable to causes other than climate change.

Pollutants of concern in this case include sediment, nutrients, organic matter, pathogens, pesticides, salt, and thermal pollution (Kundzewicz et al., 2007). IPCC (Kundzewicz et al., 2007) reviewed several studies discussing the impacts of climate change on water quality that showed:

 • In lakes and reservoirs, climate change effects are primarily caused by water temperature variations. These variations can be caused by climate change or indirectly through increases in thermal pollution as a result of higher demand for cooling water in the energy sector. This affects, for the U.S. and all world regions, dissolved oxygen regimes, redox potentials⁶⁷, lake stratification, mixing rates, and the development of aquatic biota, as they all depend on water temperature. Increasing water temperature affects the self-purification capacity of rivers by reducing the amount of dissolved oxygen available for biodegradation.

• Water pollution problems are exacerbated during low flow conditions where small water quantities result in less dilution and greater concentrations of pollutants.

Heavy precipitation frequencies in the U.S. were at a minimum in the 1920s and 1930s, and have
increased through the 1990s (Field, et al., 2007). Increases in intense rain events result in the
introduction of more sediment, nutrients, pathogens, and toxics into water bodies from non-point
sources but they also provide the pulse flow needed for some ecosystems.

North American simulations of future surface and bottom water temperatures of lakes, reservoirs, rivers, and estuaries consistently increase, with summer surface temperatures exceeding 30°C in midwestern and southern lakes and reservoirs. IPCC projects that warming is likely to extend and intensify summer thermal stratification in surface waters, further contributing to oxygen depletion (Field et al., 2007 and references therein).

Higher water temperature and variations in runoff are likely to produce adverse changes in water quality affecting human health, ecosystems, and water uses. Elevated surface water temperatures will promote algal blooms and increases in bacteria and fungi levels. Warmer waters also transfer volatile and semi-volatile compounds (ammonia, mercury, PCBs, dioxins, pesticides) from surface water bodies to the atmosphere more rapidly (Kundzewicz et al., 2007). Although this transfer will improve water quality, air quality will be negatively impacted.

Lowering of the water levels in rivers and lakes can lead to re-suspension of bottom sediments and liberating compounds, with negative effects on water supplies (Field et al., 2007 and references therein).

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⁶⁷ Redox potential is defined as the tendency of a chemical species to acquire electrons and therefore be reduced.

These impacts may lead to a bad odor and taste in chlorinated drinking water and greater occurrence of toxins. More intense rainfall will lead to increases in suspended solids (turbidity) and pollutant levels in water bodies due to soil erosion (Kundzewicz et al., 2007). Moreover, even with enhanced phosphorus removal in wastewater treatment plants, algal growth in water bodies may increase with warming over the long term. Increasing nutrient and sediment loads due to more intense runoff events will negatively affect water quality, requiring additional treatment to render it suitable for drinking water.

Climate change is likely to make it more difficult to achieve existing water quality goals for sediment (IPCC: high confidence) because hydrologic changes affect many geomorphic processes including soil erosion, slope stability, channel erosion, and sediment transport (Field et al., 2007). IPCC reviewed a number of region-specific studies on U.S. water quality and projected that:

• Changes in precipitation may increase nitrogen loads from rivers in the Chesapeake and Delaware Bay regions by up to 50% by 2030 (Kundzewicz et al., 2007 and reference therein).

• Decreases in snowcover and increases in winter rain on bare soil will likely lengthen the erosion season and enhance erosion intensity. This will increase the potential for sediment related water quality impacts in agricultural areas without appropriate soil management techniques (Field et al., 2007 and reference therein). All studies on soil erosion suggest that increased rainfall amounts and intensities will lead to greater rates of erosion, within the U.S. and in other regions, unless protection measures are taken (Kundzewicz et al., 2007). Soil management practices (e.g., crop residue, no-till) in some regions (e.g., the Cornbelt) may not provide sufficient erosion protection against future intense precipitation and associated runoff (Field et al., 2007).

11(c) Extreme Events

There are a number of climatic and non-climatic drivers influencing flood and drought impacts. Whether risks are realized depends on several factors. Floods can be caused by intense and/or long-lasting precipitation events, rapid snowmelt, dam failure, or reduced conveyance due to ice jams or landslides. Flood magnitude and spatial extent depend on the intensity, volume, and time of precipitation, and the antecedent conditions of rivers and their drainage basins (e.g., presence of snow and ice, soil composition, level of human development, existence of dikes, dams, and reservoirs, etc.) (Kundzewicz et al., 2007).

Precipitation intensity will increase across the U.S., but particularly at mid and high latitudes where mean precipitation also increases. This will affect the risk of flash flooding and urban flooding (Kundzewicz et al., 2007). Some studies project widespread increases in extreme precipitation with greater risks of not only flooding from intense precipitation, but also droughts from greater temporal variability in precipitation. In general, projected changes in precipitation extremes are larger than changes in mean precipitation (Field et al., 2007).

The socio-economic impacts of droughts arise from the interaction between climate, natural conditions, and human factors such as changes in land use. In dry areas, excessive water withdrawals from surface and groundwater sources can exacerbate the impacts of drought (Kundzewicz et al., 2007). Although drought has been more frequent and intense in the western part of the U.S., the East is also vulnerable to droughts and attendant reductions in water supply, changes in water quality and ecosystem function, and challenges in allocation (Field et al., 2007).

In addition to the effects on water supply, extreme events, such as floods and droughts, will likely reduce water quality. Increased erosion and runoff rates during flood events will wash pollutants (e.g., organic matter, fertilizers, pesticides, heavy metals) from soils into water bodies, with subsequent impacts to

species and ecosystems. During drought events, the lack of precipitation and subsequent low flow conditions will impair water quality by reducing the amount of water available to dilute pollutants. These effects from floods and droughts will make it more difficult to achieve pollutant discharge limits and water quality goals (Kundzewicz et al., 2007).

11(d) Implications for Water Uses

There are many competing water uses in the U.S. that will be adversely impacted by climate change impacts to water supply and quality. The IPCC reviewed a number of studies describing the impacts of climate change on water uses in the U.S. which showed:

- Decreased water supply and lower water levels are likely to exacerbate challenges relating to navigation in the U.S. (Field et al., 2007). Some studies have found that low flow conditions may restrict ship loading in shallow ports and harbors (Kundzewicz et al., 2007). However, navigational benefits from climate change exist as well. For example, the navigation season for the North Sea Route is projected to increase from the current 20-30 days per year to 90-100 days by 2080 (ACIA, 2004 and references therein).
- Climate change impacts to water supply and quality will affect agricultural practices, including the increase of irrigation demand in dry regions and the aggravation of non-point source water pollution problems in areas susceptible to intense rainfall events and flooding (Field et al., 2007). For more information on climate change impacts to agriculture, please see Section 9.
- The U.S. energy sector, which relies heavily on water for generation (hydropower) and cooling capacity, will be adversely impacted by changes to water supply and quality in reservoirs and other water bodies (Wilbanks et al., 2007). For more information on climate change impacts to the energy sector, please see Section 13.
- Climate-induced environmental changes (e.g., loss of glaciers, reduced river discharge, reduced snow fall in winter) will affect park tourism, winter sport activities, inland water sports (e.g., fishing, rafting, boating), and other recreational uses dependent upon precipitation (Field et al., 2007). While the North American tourism industry acknowledges the important influence of climate, its impacts have not been analyzed comprehensively.

Section 12

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Sea Level Rise and Coastal Areas

6 7 8 This section of the document discusses areas in the U.S. vulnerable to sea level rise, associated interactions with coastal development, important coastal processes, observed and projected impacts, and how climate change effects on extreme events will impact coastal areas. Information on the observed and projected rates of sea level rise due to climate change can be found in Sections 4(g) and 6(c), respectively.

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The IPCC (Field et al., 2007) recently concluded the following when considering how climate change may affect sea level rise and coastal areas in North America:

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Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution (very high confidence). 68 Sea level is rising along much of the coast, and the rate of change will increase in the future, exacerbating the impacts of progressive inundation, storm-surge flooding, and shoreline erosion.

marshes, other coastal habitats, and dependent species are threatened by sea-level rise, fixed

structures blocking landward migration, and changes in vegetation. Population growth and rising

- Storm impacts are likely to be more severe, especially along the Gulf and Atlantic coasts. Salt
 - value of infrastructure in coastal areas increases vulnerability to climate variability and future climate change.

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Vulnerable Areas 12(a)

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Interaction with Coastal Zone Development

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31 32 Coastal population growth in deltas, barrier islands, and estuaries has led to widespread conversion of natural coastal landscapes to agriculture, and aquaculture as well as industrial and residential uses. According to NOAA (Crossett et al., 2007), approximately 153 million people (53% of the total population) lived in the 673 US coastal counties in 2003. This represents an increase of 33 million people since 1980, and by 2008, the number will rise to 160 million. This population growth, the rising value of coastal property, and the projected increases in storm intensity have increased the vulnerability of coastal areas to climate variability and future climate change (IPCC, 2007b).

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For small islands, the coastline is long relative to island area. As a result, many resources and ecosystem services are threatened by a combination of human pressures and climate change effects including sealevel rise, increases in sea surface temperature, and possible increases in extreme weather events (Mimura et al., 2007).

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42 43 Although climate change is impacting coastal systems, non-climate human impacts have been more damaging over the past century. The major non-climate impacts for the U.S. and other world regions include drainage of coastal wetlands, resource extraction 69, deforestation, introductions of invasive species, shoreline protection, and the discharge of sewage, fertilizers, and contaminants into coastal

⁶⁸ According to IPCC terminology, "very high confidence" conveys a 9 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

⁶⁹ Resource extraction activities in coastal areas include sand/coral mining, hydrocarbon production, and commercial and recreational fishing.

waters (Nicholls et al., 2007)⁷⁰. The cumulative effect of these non-climate, anthropogenic impacts increases the vulnerability of coastal systems to climate-related stressors.

Coastal Processes

Climate change and sea-level rise affect sediment transport in complex ways. Erosion and ecosystem loss is affecting many parts of the US coastline, but it remains unclear to what extent these losses result from climate change instead of land loss associated with relative sea-level rise due to subsidence and other human drivers (Nicholls et al., 2007).

Coastal wetland loss is also being observed in the U.S. where these ecosystems are squeezed between natural and artificial landward boundaries and rising sea levels, a process known as 'coastal squeeze' (Field et al., 2007). The degradation of coastal ecosystems, especially wetlands and coral reefs, can have serious implications for the well-being of societies dependent on them for goods and services (Nicholls et al., 2007). For more information regarding climate change impacts to coral reefs, see Section 14.

Engineering structures, such as bulkheads, dams, levees, and water diversions, limit sediment supply to coastal areas. Wetlands are especially threatened by sea level rise when insufficient amounts of sediment from upland watersheds are deposited on them. If sea level rises slowly, the balance between sediment supply and morphological adjustment can be maintained if a salt marsh vertically accretes⁷¹, or a lagoon infills, at the same rate. However, an acceleration in the rate of sea-level rise may mean that coastal marshes and wetlands cannot keep up, particularly where the supply of sediment is limited (e.g., where coastal floodplains are inundated after natural levees or artificial embankments are overtopped) (Nicholls et al., 2007).

Although open coasts have been the focus of research on erosion and shore stabilization technology, sheltered coastal areas in the U.S. are also vulnerable and suffer secondary effects from rising seas (NRC, 2006a). For example, barrier island erosion in Louisiana has increased the height of waves reaching the shorelines of coastal bays. This has enhanced erosion rates of beaches, tidal creeks, and adjacent wetlands. The impacts of accelerated sea-level rise on gravel beaches have received less attention than sandy beaches; however these systems are threatened by sea-level rise, even under high wetland accretion rates. The persistence of gravel and cobble-boulder beaches will also be influenced by storms, tectonic events, and other factors that build and reshape these highly dynamic shorelines (Nicholls et al., 2007).

Observed Changes

According to the IPCC, most of the world's sandy shorelines retreated during the past century and climate change induced sea-level rise is one underlying cause. To date in the U.S., more than 50% of the original salt marsh habitat has already been lost. In Mississippi and Texas, over half of the shorelines eroded at average rates of 2.6 to 3.1 m/yr since the 1970s, while 90% of the Louisiana shoreline eroded at a rate of 12.0 m/yr (Nicholls et al., 2007 and references therein).

In the Great Lakes where sea level rise is not a concern, both extremely high and low water levels resulting from changes to the hydrological cycle have been damaging and disruptive to shoreline communities (Nicholls et al., 2007). High lake water levels increase storm surge flooding, accelerate shoreline erosion, and damage industrial and commercial infrastructure located on the shore. Conversely,

⁷⁰ Nicholls et al., 2007 refers to Chapter 6, "Coastal Systems and Low-lying Areas" in IPCC's 2007 Fourth Assessment Report, Working Group II.

⁷¹ The term 'vertical accretion' is defined as the accumulation of sediments and other materials in a wetland habitat that results in build-up of the land in a vertical direction.

low lake water levels can pose problems for navigation, and expose intake/discharge pipes for electrical utilities and municipal water treatment plants, and cause unpleasant odors.

In the Arctic, coastal stability is affected by factors common to all areas (i.e., shoreline exposure, relative sea level change, climate, and local geology), and by factors specific to the high-latitudes (i.e., low temperatures, ground ice, and sea ice) (Anisimov et al., 2007). Adverse impacts have already been observed along Alaskan coasts and traditional knowledge points to widespread coastal change in Alaska. Rising temperatures in Alaska are reducing the thickness and spatial extent of sea ice. This creates more open water and allows for winds to generate stronger waves, which increase shoreline erosion. Sea level rise and thawing of coastal permafrost exacerbate this problem. Higher waves will create even greater potential for this kind of erosion damage (ACIA, 2004).

Projected Impacts

The U.S. coastline is long and diverse with a wide range of coastal characteristics. Sea level rise changes the shape and location of coastlines by moving them landward along low lying contours and exposing new areas to erosion (NRC, 2006a). Coasts subsiding due to natural or human-induced causes will experience larger relative rises in sea level. In some locations, such as deltas and coastal cities (e.g., the Mississippi delta and surrounding cities), this effect can be significant (Nicholls et al., 2007). Rapid development, including an additional 25 million people in the coastal U.S. over the next 25 years, will further reduce the resilience of coastal areas to rising sea levels (Field et al., 2007). Superimposed on the impacts of erosion and subsidence, the effects of rising sea level will exacerbate the loss of waterfront property and increase vulnerability to inundation hazards (Nicholls et al., 2007).

Up to 21% of the remaining coastal wetlands in the U.S. mid-Atlantic region are potentially at risk of inundation between 2000 and 2100 (Field et al., 2007 and reference therein). Rates of coastal wetland loss, in the Chesapeake Bay and elsewhere, will increase with accelerated sea-level rise, in part due to 'coastal squeeze' (IPCC: high confidence). Salt-marsh biodiversity is likely to decrease in north-eastern marshes through expansion of non-native species such as *Spartina alterniflora*. The IPCC (Field et al., 2007) projects that many U.S. salt marshes in less developed areas can potentially keep pace with sealevel rise through vertical accretion.

Climate change is likely to have a strong impact on saltwater intrusion into coastal sources of groundwater in the U.S. and other world regions. Sea-level rise and high rates of water withdrawal, promote the intrusion of saline water into the groundwater supplies, which adversely affects water quality. Reduced groundwater recharge associated with decreases in precipitation and increased evapotranspiration⁷², will exacerbate sea level rise effects on salinization rates (Kundzewicz et al., 2007). This effect could impose enormous costs on water treatment infrastructure (i.e., costs associated with relocating infrastructure or building desalinization capacity), especially in densely populated coastal areas. Saltwater intrusion is also projected to occur in freshwater bodies along the coast. Estuarine and mangrove ecosystems can withstand a range of salinities on a short term basis; however, they are unlikely to survive permanent exposure to high salinity environments. Saltwater intrusion into freshwater rivers has already been linked with the decline of bald cypress forests in Louisiana and cabbage palm forests in Florida. Given that these ecosystems provide a variety of ecosystem services and goods (e.g., spawning habitat for fish, pollutant filtration, sediment control, storm surge attenuation), the loss of these areas could be significant (Kundzewicz et al., 2007).

⁷² Evapotranspiration is defined as the total amount of evaporation from surface water bodies (e.g., lakes, rivers, reservoirs), soil, and plant transpiration. In this context, warmer temperatures brought on by climate change will drive greater levels of evapotranspiration.

The vulnerable nature of coastal indigenous communities to climate change arises from their geographical location, reliance on the local environment for aspects of everyday life such as diet and economy, and the current state of social, cultural, economic, and political change taking place in these regions (Anisimov et al., 2007). In northern areas of ice-rich permafrost, such as Alaska, coastal erosion rates are among the highest anywhere and could be increased by rising sea levels, forcing the issue of relocation for threatened settlements. It has been estimated that relocating the village of Kivalina, AK to a nearby site would cost US\$54 million (Anisimov et al., 2007).

For small islands, some studies suggest that sea-level rise could reduce of island size, particularly in the Pacific, raising concerns for Hawaii and other U.S. territories (Mimura et al., 2007). In some cases, accelerated coastal erosion may lead to island abandonment, as has been documented in the Chesapeake Bay. Island infrastructure tends to predominate in coastal locations. In the Caribbean and Pacific Islands, more than 50% of the population lives within 1.5 km of the shore. International airports, roads, capital cities, and other types of infrastructure, are typically sited along the coasts of these islands as well. Therefore, the socio-economic well-being of island communities will be threatened by inundation, storm surge, erosion, and other coastal hazards resulting from climate change (high confidence) (Mimura et al., 2007).

12(b) Extreme Events

Although increases in mean sea level over the 21st century and beyond will inundate unprotected, low-lying areas, the most devastating impacts are likely to be associated with storm surge (Nicholls et al., 2007). For example, the Maryland Geological Survey estimated that more than 20 acres of the State's land was lost on the western shore of Chesapeake Bay in the wake of Tropical Storm Isabel, causing approximately \$84,000,000 in damages to shoreline structures (NRC, 2006a and references therein).

Superimposed on accelerated sea level rise, storm intensity, wave height, and storm surge projections suggest more severe coastal flooding and erosion hazards (Nicholls et al., 2007). In New York City and Long Island, flooding from a combination of sea level rise and storm surge could be several meters deep (Field et al., 2007). Projections suggest that the return period of a 100-year flood event in this area might be reduced to 19-68 years, on average, by the 2050s, and to 4-60 years by the 2080s (Wilbanks et al., 2007; and references therein).

Additionally, some major urban centers in the U.S. are situated in low-lying flood plains. For example, areas of New Orleans and its vicinity are 1.5-3 meters below sea level. Considering the rate of subsidence and using a mid-range estimate of 480 millimeters sea-level rise by 2100, it is projected that this region could be 2.5 to 4.0 meters or more below mean sea level by 2100 (Field et al., 2007). In this scenario, a storm surge from a Category 3 hurricane (estimated at 3 to 4 meters without waves) could be six to seven meters above areas that were heavily populated in 2004 (Field et al., 2007 and references therein).

The IPCC discusses a number of other extreme event scenarios and observations with implications for coastal areas of the US:

- Very large sea-level rises that would result from widespread deglaciation of Greenland and West Antarctic ice sheets imply major changes in coastlines and ecosystems, and inundation of low-lying areas, with greatest effects in river deltas. Relocating populations, economic activity, and infrastructure would be costly and challenging (IPCC, 2007b).
- Under El Niño conditions, high water levels combined with changes in winter storms along the Pacific coast have produced severe coastal flooding and storm impacts. In San Francisco, 140 years of tide-gauge data suggest an increase in severe winter storms since 1950 and some studies have detected accelerated coastal erosion (Field et al., 2007).

- Recent winters with less ice in the Great Lakes and Gulf of St. Lawrence have increased coastal exposure to damage from winter storms (Field et al., 2007).
- Recent severe tropical and extra-tropical storms demonstrate that North American urban centers with assumed high adaptive capacity remain vulnerable to extreme events (Field et al., 2007).

Demand for waterfront property and building land in the U.S. continues to grow, increasing the value of property at risk. Of the \$19 trillion value of all insured residential and commercial property in the US states exposed to North Atlantic hurricanes, \$7.2 trillion (41%) is located in coastal counties. This economic value includes 79% of the property in Florida, 63% of property in New York, and 61% of the property in Connecticut (AIR, 2002 in Field et al., 2007). The devastating effects of hurricanes Ivan in 2004 and Katrina, Rita and Wilma in 2005 illustrate the vulnerability of North American infrastructure and urban systems that were not designed or not maintained to adequate safety margins. When protective systems fail, impacts can be widespread and multi-dimensional (Field et al., 2007).

Section 13

Energy, Infrastructure and Settlements

According to IPCC (Wilbanks et al., 2007), "[i]ndustries, settlements and human society are accustomed to variability in environmental conditions, and in many ways they have become resilient to it when it is a part of their normal experience. Environmental changes that are more extreme or persistent than that experience, however, can lead to vulnerabilities, especially if the changes are not foreseen and/or if capacities for adaptation are limited."

Climate change is likely⁷³ to affect U.S. energy use and energy production; physical infrastructures; institutional infrastructures; and will likely interact with and possibly exacerbate ongoing environmental change and environmental pressures in settlements (Wilbanks et al., 2007), particularly in Alaska where indigenous communities are facing major environmental and cultural impacts on their historic lifestyles (ACIA, 2004). The research evidence is relatively clear that climate warming will mean reductions in total U.S. heating requirements and increases in total cooling requirements for buildings. These changes will vary by region and by season, but they will affect household and business energy costs and their demands on energy supply institutions. In general, the changes imply increased demands for electricity, which supplies virtually all cooling energy services but only some heating services. Other effects on energy consumption are less clear (CCSP, 2007a).

13(a) Heating and Cooling Requirements

With climate warming, less heating is required for industrial, commercial, and residential buildings in the U.S., but more cooling is required, with changes varying by region and by season. Net energy demand at a national scale will be influenced by the structure of the energy supply. The main source of energy for cooling is electricity, while coal, oil, gas, biomass, and electricity are used for space heating. Regions with substantial requirements for both cooling and heating could find that net annual electricity demands increase while demands for other heating energy sources decline. Critical factors for the U.S. are the relative efficiency of space cooling in summer compared to space heating in winter, and the relative distribution of populations in colder northern or warmer southern regions. Seasonal variation in total demand is also important. In some cases, due to infrastructure limitations, peak demand could go beyond the maximum capacity of the electricity transmission system (Wilbanks et al., 2007).

Recent North American studies generally confirm earlier work showing a small net change (increase or decrease, depending on methods, scenarios, and location) in net demand for energy in buildings but a significant increase in demand for electricity for space cooling, with further increases caused by additional market penetration of air conditioning (high confidence) (Field et al., 2007). Generally speaking, the net effects of climate change in the U.S. on total energy demand are projected to amount to between perhaps a 5% increase and decrease in demand per 1°C in warming in buildings. Existing studies do not agree on whether there would be a net increase or decrease in energy consumption with changed climate because a variety of methodologies have been used (CCSP, 2007a).

In California, if temperatures rise according to a high scenario range (8-10.5°F; ~4.5-5.6°C), annual electricity demand for air conditioning could increase by as much as 20% by the end of the century (assuming population remains unchanged and limited implementation of efficiency measures) (California

 $^{^{73}}$ According to IPCC terminology, "likely" conveys a 66 to 90% probability of occurrence. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

Energy Commission, 2006)⁷⁴. In Alaska, there will be savings on heating costs: modeling has predicted a 15% decline in the demand for heating energy in the populated parts of the Arctic and sub-Arctic and up to one month decrease in the duration of a period when heating is needed (Anisimov et al., 2007).

Overall, both net delivered energy and net primary energy consumption increase or decrease only a few percent with a 1°C or 2°C warming; however, there is a robust result that, in the absence of an energy efficiency policy directed at space cooling, climate change would cause a significant increase in the demand for electricity in the U.S., which would require the building of additional electricity generation capacity (and probably transmission facilities) worth many billions of dollars (CCSP, 2007a).

Beyond the general changes described above, general temperature increases can mean changes in energy consumption in key climate-sensitive sectors of the economy, such as transportation, construction, agriculture, and others. Furthermore, there may be increases in energy used to supply other resources for climate-sensitive processes, such as pumping water for irrigated agriculture and municipal uses (CENR, 2008).

13(b) Energy Production

Climate change could affect U.S. energy production and supply (a) if extreme weather events become more intense, (b) where regions dependent on water supplies for hydropower and/or thermal power plant cooling face reductions or increases in water supplies, (c) where changed conditions affect facility siting decisions, and (d) where climatic conditions change (positively or negatively) for biomass, wind power, or solar energy production (Wilbanks et al., 2007; CCSP 2007a).

Significant uncertainty exists about the potential impacts of climate change on energy production and distribution, in part because the timing and magnitude of climate impacts are uncertain. Nonetheless, every existing source of energy in the U.S. has some vulnerability to climate variability. Renewable energy sources tend to be more sensitive to climate variables; but fossil energy production can also be adversely effected by air and water temperatures, and the thermoelectric cooling process that is critical to maintaining high electrical generation efficiencies also applies to nuclear energy. In addition, extreme weather events have adverse effects on energy production, distribution, and fuel transportation (CCSP, 2007a).

Fossil and Nuclear Energy

Climate change impacts on U.S. electricity generation at fossil and nuclear power plants are likely to be similar. The most direct climate impacts are related to power plant cooling and water availability. As currently designed, power plants require significant amounts of water, and they will be vulnerable to fluctuations in water supply. Regional scale changes would likely mean that some areas would see significant increases in water availability while other regions would see significant decreases. In those areas seeing a decline, the impact on power plant availability or even siting of new capacity could be significant. Plant designs are flexible and new technologies for water reuse, heat rejection, and use of alternative water sources are being developed; but, at present, some impact—significant on a local level—can be foreseen (CCSP, 2007a).

Renewable Energy

⁷⁴ Temperature projections for the State of California are based on IPCC global emission scenarios as discussed in Section 6(a).

Because renewable energy depends directly on ambient natural resources such as hydrological resources, wind patterns and intensity, and solar radiation, it is likely to be more sensitive to climate variability than fossil or nuclear energy systems that rely on geological stores. Renewable energy systems in the U.S. are also vulnerable to damage from extreme weather events (CCSP, 2007a).

Hydropower generation is sensitive to the amount, timing, and geographical pattern of precipitation as well as temperature (rain or snow, timing of melting). Reduced stream flows are expected to jeopardize hydropower production in some areas of the U.S., whereas greater stream flows, depending on their timing, might be beneficial (Wilbanks et al., 2007). In California, where hydropower now comprises about 15% of in-state energy production, diminished snow melt flowing through dams will decrease the potential for hydropower production by up to 30% if temperatures rise to the medium warming range by the end of the century (5.5-8°F (~3.1-4.4°C) increase in California) and precipitation decreases by 10 to 20%. However, future precipitation projections are quite uncertain so it is possible that precipitation may increase and expand hydropower generation (California Energy Commission, 2006).

North American wind and solar resources are about as likely as not to increase (medium confidence). Studies to date project wind resources that are either unchanged by climate change, or reduced by 0-40%. Future changes in cloudiness could slightly increase the potential for solar energy in North America south of 60°N, but one study projected that increased cloudiness will likely decrease the output of photovoltaics by 0-20% (Field et al., 2007).

Bioenergy potential is climate-sensitive through direct impacts on crop growth and availability of irrigation water. Warming and precipitation increases are expected to allow the bioenergy crop switchgrass, for instance, to compete effectively with traditional crops in the central U.S (Field et al., 2007). Renewable energy production is highly susceptible to localized and regional changes in the resource base. As a result, the greater uncertainties on regional impacts under current climate change modeling pose a significant challenge in evaluating medium to long-term impacts on renewable energy production (CCSP, 2007a).

Energy Supply and Transmission

Extreme weather events can threaten coastal energy infrastructures and electricity transmission and distribution infrastructures in the U.S. and other world regions (Wilbanks et al., 2007). Hurricanes in particular can have severe impacts on energy infrastructure. In 2004, hurricane Ivan destroyed seven Gulf of Mexico oil drilling platforms and damaged 102 pipelines, while hurricanes Katrina and Rita in 2005 destroyed more than 100 platforms and damaged 558 pipelines (CCSP, 2007a). Though it is not possible to attribute the occurrence of any singular hurricane to climate change, projections of climate change suggest that extreme weather events are very likely to become more intense. If so, then the impacts of Katrina may be a possible indicator of the kinds of impacts that could manifest as a result of climate change (CCSP, 2007a).

In addition to the direct effects on operating facilities themselves, U.S. networks for transport, electric transmission, and delivery would be susceptible to changes due to climate change in stream flow, annual and seasonal precipitation patterns, storm severity, and even temperature increases (e.g., pipelines handling supercritical fluids may be impacted by greater heat loads) (CCSP, 2007a).

U.S. rail transportation lines, which transport approximately 2/3 of the coal to the nation's power plants (EIA, 2002; as referenced in CCSP, 2007a), often closely follow riverbeds. More severe rainstorms can lead to flooding of rivers which then can wash out or degrade the nearby roadbeds. Flooding may also disrupt the operation of inland waterways, the second-most important method of transporting coal. With utilities carrying smaller stockpiles and projections showing a growing reliance on coal for a majority of

the nation's electricity production, any significant disruption to the transportation network has serious implications for the overall reliability of the grid as a whole. (CCSP, 2007a)

In the Arctic, soil subsidence caused by the melting of permafrost is a risk to gas and oil pipelines, electrical transmission towers, and natural gas processing plants (Wilbanks et al., 2007). Along the Beaufort Sea in Alaska, climate impacts on oil and gas development in the region are likely to result in both financial benefits and costs in the future. For example, offshore oil exploration and production are likely to benefit from less extensive and thinner sea ice, although equipment will have to be designed to withstand increased wave forces and ice movement (ACIA, 2004).

13(c) Infrastructure and Settlements

Climate change vulnerabilities of industry, settlement and society are mainly related to extreme weather events rather than to gradual climate change. The significance of gradual climate change, e.g., increases in the mean temperature, lies mainly in changes in the intensity and frequency of extreme events, although gradual changes can also be associated with thresholds beyond which impacts become significant, such as in the capacities of infrastructures (Field et al., 2007).

Extreme weather events could threaten U.S. coastal energy infrastructure and electricity transmission and distribution infrastructures. Moreover, soil subsidence caused by the melting of permafrost in the Arctic region is a risk to gas and oil pipelines, and electrical transmission towers. Vulnerabilities of industry, infrastructures, settlements and society to climate change are generally greater in certain high-risk locations, particularly coastal and riverine areas, and areas whose economies are closely linked with climate-sensitive resources, such as agricultural and forest product industries, water demands and tourism; these vulnerabilities tend to be localized but are often large and growing (high confidence) (Wilbanks et al., 2007).

A few studies have projected increasing vulnerability of U.S. infrastructure to extreme weather related to climate warming unless adaptation is effective (high confidence). Examples include the New York Metropolitan Region, the mid-Atlantic Region, and the urban transportation network of the Boston metropolitan area (Wilbanks et al., 2007). In Alaska, examples where infrastructure is projected to be at "moderate to high hazard" in the mid-21st century include Shishmaref, Nome, Barrow, the Dalton Highway, and the Alaska Railroad (Field et al., 2007). Where extreme weather events become more intense and/or more frequent with climate change, the economic and social costs of those events will increase (high confidence) (Wilbanks et al., 2007).

Buildings and Construction

In some Arctic areas, interactions between climate warming and inadequate engineering are causing problems. The weight of buildings on permafrost is an important factor; while many heavy, multi-story buildings of northern Russia have suffered structural failures, the lighter-weight buildings of North America have had fewer such problems as permafrost has warmed. Continuous repair and maintenance is also required for building on permafrost, a lesson learned because many of the buildings that failed were not properly maintained. The problems now being experienced in Russia may be expected to occur elsewhere in the Arctic if buildings are not designed and maintained to accommodate future warming (ACIA, 2004).

The cost of rehabilitating community infrastructure damaged by thawing permafrost could be significant. Even buildings designed specifically for permafrost environments may be subject to severe damage if design criteria are exceeded. The impervious nature of ice-rich permafrost has been relied on for

contaminant holding facilities, and thawing such areas could result in severe contamination of hydrological resources and large cleanup costs, even for relatively small spills (Anisimov et al., 2007).

The construction season in the northern U.S. likely will lengthen with warming. In permafrost areas in Alaska, increasing depth of the "active layer" or loss of permafrost can lead to substantial decreases in soil strength. Construction methods are likely to require changes in areas currently underlain by permafrost, potentially increasing construction and maintenance cost (high confidence) (Field et al., 2007).

8 2007).9 Transportation

In a 2008 report entitled, "Potential Impacts of Climate Change on U.S. Transportation," the National Research Council (NRC) issued the following finding:

Climate change will affect transportation primarily through increases in several types of weather and climate extremes, such as very hot days; intense precipitation events; intense hurricanes; drought; and rising sea levels, coupled with storm surges and land subsidence. The impacts will vary by mode of transportation and region of the country, but they will be widespread and costly in both human and economic terms and will require significant changes in the planning, design, construction, operation, and maintenance of transportation systems (NRC, 2008).

NRC states that transportation infrastructure was designed for typical weather patterns, reflecting local climate and incorporating assumptions about a reasonable range of temperatures and precipitation levels (NRC, 2008). An increase in the frequency, intensity, or duration of heat spells in the U.S. and other world regions could cause railroad tracks to buckle, and affect roads through softening and traffic-related rutting. Warmer or less snowy winters will likely reduce delays, improve ground and air transportation reliability, and decrease the need for winter road maintenance. More intense winter storms could, however, increase risk for traveler safety and require increased snow removal. Continuation of the declining fog trend in at least some parts of North America should benefit transport (Field et al., 2007).

Warming will likely affect infrastructure for surface transport at high northern latitudes, such as Alaska. Permafrost degradation reduces surface bearing capacity and potentially triggers landslides. While the season for transport by barge is likely to be extended, the season for ice roads will likely be compressed. Other types of roads are likely to incur costly improvements in design and construction (Field et al., 2007).

Similarly, NRC found the following:

Potentially, the greatest impact of climate change for North America's transportation systems will be flooding of coastal roads, railways, transit systems, and runways because of global rising sea levels, coupled with storm surges and exacerbated in some locations by land subsidence (NRC, 2008).

Because of warming, the number of days per year in which travel on the tundra is allowed under Alaska Department of Natural Resources standards has dropped from over 200 to about 100 in the past 30 years, resulting in a 50% reduction in days that oil and gas exploration and extraction can occur (ACIA, 2004). Forestry is another industry that requires frozen ground and rivers. Higher temperatures mean thinner ice on rivers and a longer period during which the ground is thawed. This leads to a shortened period during which timber can be moved from forests to sawmills, and increasing problems associated with transporting wood (ACIA, 2004).

Lakes and river ice have historically provided major, winter transportation routes and connections to smaller settlements in the Arctic. Reductions in ice thickness will reduce the load-bearing capacity, and

shortening of the ice-season will shorten period of access. Where an open-water network is viable, it will be sensible to increase reliance on water transport. In land locked locations, construction of all-weather roads may be the only viable option, with implications for significantly increased costs. Similar issues will impact the use of sea ice roads primarily used to access offshore facilities (Anisimov et al., 2007). Loss of summer sea ice will bring an increasingly navigable Northwest Passage. Increased marine navigation and longer summers will improve conditions for tourism and travel associated with research (Anisimov et al., 2007). Along with rising water temperatures, however, increased shipping will also multiply the risk of marine pests and pollution (Anisimov et al., 2007).

Negative impacts on transportation very likely will include coastal and riverine flooding and landslides. Although offset to some degree by fewer ice threats to navigation, reduced water depth in the Great Lakes would lead to "light loading" and adverse economic impacts (Field et al., 2007).

Of all the possible impacts on transportation, the greatest in terms of cost is that of flooding. The costs of delays and lost trips would be relatively small compared with damage to the infrastructure and to other property (Wilbanks et al., 2007).

The central Gulf Coast is particularly vulnerable to climate variability and change because of the frequency with which hurricanes strike, because much of its land is sinking relative to mean sea level, and because much of its natural protection—in the form of barrier islands and wetlands—has been lost. While difficult to quantify, the loss of natural storm buffers will likely intensify many climate impacts, particularly in relation to storm damage (CCSP, 2008b).

Since much of the land in the Gulf Coast is sinking, this area is facing much higher increases in relative sea level rise (the combination of local land surface movement and change in mean sea level) than most other parts of the U.S. coast. The CCSP report found that relative sea level rise in the study area is very likely to increase by at least 0.3 m (1 ft) across the region and possibly as much as 2 m (6 to 7 ft) in some parts of the study area over the next 50 to 100 years. The analysis of even a middle range of potential sea level rise of 0.3 to 0.9 m (2 to 4 ft) indicates that a vast portion of the Gulf Coast from Houston to Mobile may be inundated in the future. The projected rate of relative sea level rise for the region during the next 50 to 100 years is consistent with historical trends, region-specific analyses, and the IPCC Fourth Assessment Report (2007) findings, which assume no major changes in ice-sheet dynamics (CCSP, 2008b).

Twenty-seven percent of the major roads, 9 percent of the rail lines, and 72 percent of the ports in the region are at or below 122 cm (4 ft) in elevation, although portions of the infrastructure are guarded by protective structures such as levees and dikes. These protective structures could mitigate some impacts, but considerable land area is still at risk to permanent flooding from rising tides, sinking land, and erosion during storms. Furthermore, the crucial connectivity of the intermodal system in the area means that the services of the network can be threatened even if small segments are inundated (CCSP, 2008b).

A great deal of the Gulf Coast study area's infrastructure is subject to temporary flooding associated with storm surge. More than half (64 percent of interstates; 57 percent of arterials) of the area's major highways, almost half of the rail miles, 29 airports, and virtually all of the ports are subject to flooding based on the study of a 5.5- and 7.0-m (18- and 23-ft) storm surge (CCSP, 2008b).

Aviation may also be affected. Increases in precipitation and the frequency of severe weather events could negatively affect aviation. Higher temperatures affect aircraft performance and increase the necessary runway lengths. Some of these risks are expected to be offset by improvements in technology and information systems (CENR, 2008).

Settlements

According to IPCC (2007b), "The most vulnerable industries, settlements and societies are generally those in coastal and river flood plains, those whose economies are closely linked with climate-sensitive resources, and those in areas prone to extreme weather events, especially where rapid urbanization is occurring (high confidence). Poor communities can be especially vulnerable, in particular those concentrated in high-risk areas. They tend to have more limited adaptive capacities, and are more dependent on climate-sensitive resources such as local water and food supplies (high confidence)".

Effects of climate change on human settlements in the U.S. are very likely to vary considerably according to location-specific vulnerabilities, with the most vulnerable areas likely to include: Alaska, flood-risk coastal zones and river basins, arid areas with associated water scarcity and areas where the economic base is climate sensitive (CCSP, 2007a).

In Alaska and elsewhere in the Arctic, indigenous communities are facing major economic and cultural impacts. Many indigenous peoples depend on hunting polar bear, walrus, seals, and caribou, and herding reindeer, fishing and gathering, not only for food and to support the local economy, but also as the basis for cultural and social identity. Changes in species' ranges and availability, access to these species, a perceived reduction in weather predictability, and travel safety in changing ice and weather conditions present serious challenges to human health and food security, and possibly even the survival of some cultures (ACIA, 2004).

Communities in risk-prone U.S. regions have reason to be particularly concerned about any potential increase in severe weather events. The combined effects of severe storms and sea-level rise in coastal areas or increased risks of fire in drier arid areas are examples of how climate change may increase the magnitude of challenges already facing risk-prone communities. Vulnerabilities may be especially great for rapidly-growing and/or larger metropolitan areas, where the potential magnitude of both impacts and coping requirements are likely to be very large. On the other hand, such regions have greater opportunity to put more adaptable infrastructure in place and make decisions that limit vulnerability (CCSP, 2007a).

Climate change has the potential not only to affect U.S. communities directly but also through undermining their economic bases. In particular, some regional economies are dependent on sectors highly sensitive to changes in climate: agriculture, forestry, water resources, or tourism. Climate change can add to stress on social and political structures by increasing management and budget requirements for public services such as public health care, disaster risk reduction, and even public safety. As sources of stress grow and combine, the resilience of social and political structures are expected to suffer, especially in locales with relatively limited social and political capital (CCSP, 2007a).

Finally, growth and development is generally moving toward areas more likely to be vulnerable to the effects of climate change. For example, approximately half of the U.S. population, 160 million people, will live in one of 673 coastal counties by 2008. Coastal areas – particularly those on gently-sloping coasts – should be concerned about sea level rise in the longer term, especially if they are subject to severe storms and storm surges and/or if their regions are showing gradual land subsidence. Areas that have been classified as highly vulnerable to climate change (based on measures of physical vulnerability and adaptive capacity) include counties lying along the east and west coasts and Great Lakes, with medium vulnerability counties mostly inland in the southeast, southwest, and northeast (CCSP, 2007a).

Section 14

2 3

Ecosystems and Wildlife

This Section of the document covers: 1) ecosystem and species-level impacts due to climate change and elevated CO_2 levels, 2) implications for ecosystem services, 3) how climate change effects on extreme event frequency and intensity may impact ecosystems, and 4) impacts to tourism and recreation.

For North America, the IPCC (Field et al., 2007; Fischlin et al., 2007⁷⁵) concluded:

• Disturbances such as wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons (very high confidence). Although recent climate trends have increased vegetation growth, continuing increases in disturbances are likely to limit carbon storage, facilitate invasive species, and disrupt ecosystem services. Over the 21st century, changes in climate will cause species to shift north and to higher elevations and fundamentally rearrange North American ecosystems. Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections will alter ecosystem structure, function, and services.

14(a) Ecosystems and Species

Ecosystems, plants, and animals are sensitive to climate variability and always have been. Three clearly observable connections between climate and terrestrial ecosystems are the seasonal timing of life-cycle events (referred to as phenology), responses of plant growth or primary production, and the biogeographic distribution of species (see Figure 14.1).

IPCC reviewed a number of studies describing observations of climate change effects on plant species: (Field, et al., 2007 and references therein):

- Between 1981 and 2000, global daily satellite data indicate earlier onset of spring "greenness" by 10-14 days, particularly across temperate latitudes of the Northern Hemisphere. Field studies conducted in the same areas confirm these satellite observations.
- Leaves are expanding earlier (e.g., apple and grape plants--2 days/decade at 72 sites in Northeastern U.S.).
 - Flowering plants are blooming earlier (e.g., lilac 1.8 days/decade earlier from 1959-1993, at 800 sites across North America, honeysuckle -- 3.8 days/decade earlier in the western U.S.).
- The timing of autumn leaf senescence⁷⁷, which is controlled by a combination of temperature, photoperiod and water deficits, shows weaker trends.

IPCC also discussed several studies showing how North American animals are responding to climate change, with effects on phenology, migration, reproduction, dormancy, and geographic range (Field, et al., 2007 and references therein):

⁷⁵ Fischlin et al., 2007 citation refers to Chapter 4, "Ecosystems, Their Properties, Goods, and Services" in IPCC's 2007 Fourth Assessment Report, Working Group II.

⁷⁶ According to IPCC terminology, "very high confidence" conveys a 9 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

⁷⁷ The term 'senescence' is defined as the last stage of leaf development that includes changes in pigment expression, cell death, and eventual leaf drop.

- Warmer springs have led to earlier nesting for 28 migrating bird species on the East coast of the U.S. and to earlier egg laying for Mexican jays and tree swallows.
- Several frog species now initiate breeding calls 10-13 days earlier than a century ago.
- In lowland California, 16 of 23 butterfly species advanced the date of first spring flights an average 24 days over 31 years.
 - Reduced water depth, related to recent warming, in Oregon lakes has increased exposure of toad eggs to UV-B, leading to increased mortality from a fungal parasite.
 - The Edith's checkerspot butterfly has become locally extinct in the southern, low elevation portion of its western North American range, but has extended its range 90 km north and 120 m higher in elevation.

Many North American species, like the Edith's checkerspot butterfly, have shifted their ranges, typically to the north or to higher elevations. Migrating to higher elevations with more suitable temperatures can be an effective strategy for species if habitat connectivity ⁷⁸ exists and other biotic and abiotic conditions are appropriate. However, many organisms cannot shift their ranges fast enough to keep up with the current pace of climate change. In addition, species that require higher-elevation habitat, such as alpine ecosystems, often have nowhere to migrate.

The direct effects of elevated CO₂ concentrations and climate change to marine ecosystems include ocean warming, increased thermal stratification, reduced upwelling, sea level rise, increased wave height and frequency, loss of sea ice, increased risk of diseases in marine biota, and decreases in the pH and carbonate ion concentration of the surface oceans. With lower pH, aragonite (calcium carbonate) that is used by many organisms to make their shells or skeletons will decline or become under-saturated, affecting coral reefs, and other marine calcifiers (e.g., pteropods-marine snails). Additional synergistic impacts of higher seawater temperatures (average changes and high temperature bleaching events) will make these ecosystems even more vulnerable to changes in ocean chemistry along the U.S. and other world regions (Fischlin, et al., 2007). The effects of various other stressors, particularly human impacts such as overfishing, pollution, and the introduction of invasive species, appear to be exacerbating the thermal stresses on reef systems and, at least on a local scale, exceeding the thresholds beyond which coral is replaced by other organisms (Nicholls, et al., 2007).

In the Bering Sea along the Alaskan coast, rising air and sea water temperatures have caused reductions in sea-ice cover and primary productivity in benthic ecosystems⁷⁹. A change from Arctic to sub-Arctic conditions is happening with a northward movement of the pelagic-dominated marine ecosystem that was previously confined to the Southeastern Bering Sea (Anisimov, et al., 2007). Climate-related impacts observed in the Bering Sea include significant reductions in seabird and marine mammal populations, increases in pelagic fish, occurrences of previously rare algal blooms, abnormally high water temperatures, and smaller salmon runs in coastal rivers (ACIA, 2004). Plants and animals in polar regions are also vulnerable to attacks from pests and parasites that develop faster and are more prolific in warmer and moister conditions (Anisimov, et al., 2007). See Box 14.1 for more information on potential climate change impacts to polar bears.

Ecosystem Level Projections

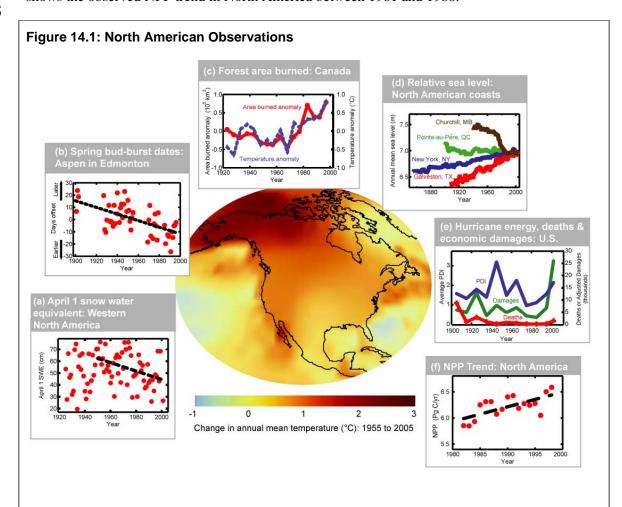
For terrestrial ecosystems across all world regions, the IPCC concluded that substantial changes in structure and functioning of terrestrial ecosystems are very likely to occur with a global warming greater

⁷⁸ Connectivity is defined as the degree to which a habitat is physically linked with other suitable areas for a particular species.

Benthic is defined as the deepest environment of a water body which usually includes the seabed or lake floor.

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than 2 to 3°C above pre-industrial levels (high confidence) (Fischlin, et al., 2007). In North America, disturbances like wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons (very high confidence) (Field, et al., 2007). Figure 14.1 shows the observed NPP trend in North America between 1981 and 1988.



Change in annual mean temperature from 1955 to 2005 (based on the GISS2001 analysis for land from Hansen et al., 2001; and on the Hadley/Reyn_V2 analysis for sea surface from Reynolds et al., 2002). Insets: (a) trend in April 1 SWE across western North America from 1925-2002, with a linear fit from 1950-2002 (data from Mote, 2003), (b) Spring bud-burst dates for trembling aspen in Edmonton since 1900 (data from Beaubien and Freeland, 2000), (c) anomaly in 5-year mean area burned annually in wildfires in Canada since 1930, plus observed mean summer air temperature anomaly, weighted for fire areas, relative to 1920-1999 (data from Gillett et al., 2004) (d) relative sea level rise from 1850-2000 for Churchill, MB, Pointe-au-Père, QB, New York, NY, and Galveston, TX, (POL, 2006) (e) hurricane energy (PDI), economic damages, and deaths from Atlantic hurricanes since 1900 (data from Pielke Jr. and Landsea, 1999 updated through 2005; Emanuel, 2005; Saunders and Lea, 2005 updated through 2005), and, (f) trend North American NPP (Net Primary Productivity) from 1981 to 1998 (data from Hicke et al., 2002).

At high latitudes, several models project longer growing seasons and increased net primary productivity (NPP) as a result of forest expansion into tundra ecosystems. In the mid latitudes, simulated changes in NPP are variable, depending on whether there is sufficient enhancement of precipitation to offset increased evapotranspiration in a warmer climate. By the end of the 21st century, ecosystems in the northeast and southeast U.S. are projected to become carbon sources, while the western U.S. remains a carbon sink (Field, et al., 2007).

The aerial extent of drought-limited ecosystems is projected to increase 11% per °C warming in the continental U.S. Climate change and direct human land-use pressures are likely to both have adverse impacts on desert ecosystems and species. Increases in plant productivity resulting from the direct effects of rising atmospheric CO₂ concentrations may partially offset these adverse effects. In California, temperature increases greater than 2°C may lead to the conversion of shrubland into desert and grassland ecosystems and evergreen conifer forests into mixed deciduous forests (Fischlin, et al., 2007).

The sea-ice biome accounts for a large proportion of primary production in polar waters and supports a substantial food web. In the Northern Hemisphere, projections of ocean biological response to climate warming by 2050 show contraction of the highly productive marginal sea ice biome by 42% (Fischlin, et al., 2007). In the Bering Sea, primary productivity in surface waters is projected to increase, the ranges of some cold-water species will shift north, and ice-dwelling species will experience habitat loss (ACIA, 2004).

Species Level Projections

After reviewing studies on the projected impacts of climate change on species, IPCC concluded that on a global scale (Fischlin et al., 2007 and references therein):

• Projected impacts on biodiversity are significant and of key relevance, since global losses in biodiversity are irreversible (very high confidence).

• Endemic species⁸⁰ richness is highest where regional palaeoclimatic changes have been subtle, providing circumstantial evidence of their vulnerability to projected climate change (medium confidence). With global average temperature changes of 2°C above pre-industrial levels many terrestrial, freshwater, and marine species (particularly endemics across the globe) are at a far greater risk of extinction than in the geological past (medium confidence).

 • Approximately 20% to 30% of species (global uncertainty range from 10% to 40%, but varying among regional biota from as low as 1% to as high as 80%) will be at increasingly high risk of extinction by 2100.

In North America, climate change impacts on inland aquatic ecosystems will range from the direct effects of increased temperature and CO_2 concentration to indirect effects associated with alterations in hydrological systems resulting from changes to precipitation regimes and melting glaciers and snow pack (Fischlin et al., 2007). For many freshwater animals, such as amphibians, migration to breeding ponds and the production of eggs is intimately tied to temperature and moisture availability. Asynchronous timing of breeding cycles and pond drying due to the lack of precipitation can lead to reproductive failure. Differential responses among species in arrival or persistence in ponds will likely lead to changes in community composition and nutrient flow in ponds (Fischlin et al., 2007).

Bioclimate modeling based on output from five general circulation models (GCMs) suggests that, over the next century, vertebrate and tree species richness will decrease in most parts of the conterminous U.S.,

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⁸⁰ Endemic species are unique to their location or region and are not found anywhere else on Earth.

even though long-term trends (millennia scale) ultimately favor increased richness in some taxa and locations (Field et al., 2007). Changes in plant species composition in response to climate change can increase ecosystem vulnerability to other disturbances, including fire and biological invasion.

On small oceanic islands with cloud forests or high elevation ecosystems, such as the Hawaiian Islands, extreme elevation gradients exist, ranging from nearly tropical to alpine environments. In these ecosystems, anthropogenic climate change, land-use changes, and biological invasions will work synergistically to drive several species (e.g., endemic birds) to extinction (Mimura et al., 2007).

According to IPCC, climate change (very high confidence) and ocean acidification due to the direct effects of elevated CO₂ concentrations (medium confidence) will impair a wide range of planktonic and other marine organisms that use aragonite to make their shells or skeletons (Fischlin et al., 2007). These impacts could result in potentially severe ecological changes to tropical and coldwater marine ecosystems where carbonate-based phytoplankton and corals are the foundation for the trophic system (Schneider et al., 2007). The IPCC concluded that it is very likely that a projected future sea surface temperature increase of 1 to 3°C will result in more frequent bleaching events and widespread mortality, if there is not thermal adaptation or acclimatization by corals and their algal symbionts. However, the ability of coral reef ecosystems to withstand the impacts of climate change will depend to a large degree on the extent of degradation from other anthropogenic pressures and the frequency of future bleaching events (Nicholls et al., 2007).

For the Arctic, IPCC (Anisimov et al., 2007 and references therein) concluded that:

• Decreases in the abundance of keystone species⁸¹ are expected to be the primary factor in causing ecological cascades⁸² and other changes to ecological dynamics.

• Arctic animals are likely to be most vulnerable to warming-induced drying of small water bodies; changes in snow cover and freeze-thaw cycles that affect access to food (e.g., polar bear dependence on sea ice for seal hunting) and protection from predators (e.g., snow rabbit camouflage in snow); changes that affect the timing of behavior (e.g., migration and reproduction); and influx of new competitors, predators, parasites, and diseases.

• In the past, sub-arctic species have been unable to live at higher latitudes because of harsh conditions. Climate change induced warming will increase the rate at which sub-arctic species are able to establish. Some non-native species, such as the North American mink, will become invasive, while other species that have already colonized some Arctic areas are likely to expand into other regions. The spread of non-native, invasive plants will likely have adverse impacts on native plant species. For example, experimental warming and nutrient addition has showed that native mosses and lichens become less abundant when non-native plant biomass increases.

• Bird migration routes and timing are likely to change as the availability of suitable habitat in the Arctic decreases.

Loss of sea ice will impact species, such as harp seals, which are dependent on it for survival.

 • Climate warming is likely to increase the incidence of pests, parasites, and diseases such as musk ox lung worm and abomasal nematodes of reindeer.

⁸¹ Keystone species is defined as a species that has a disproportionate effect on its environment relative to its abundance or total biomass. Typically, ecosystems experience dramatic changes with the removal of such a species. ⁸² Ecological cascades are defined as sequential chains of ecological effects, including starvation and death, beginning at the bottom levels of the food chain and ascending to higher levels, including apex predators.

Box 14.1: Polar bears

There are an estimated 20,000 to 25,000 polar bears (Ursus maritimus) worldwide, mostly inhabiting the annual sea ice over the continental shelves and inter-island archipelagos of the circumpolar Arctic. Polar bears are specialized predators that hunt ice-breeding seals and are therefore dependent on sea ice for survival. After emerging in spring from a 5 to 7 month fast in nursing dens, females require immediate nourishment and thus depend on close proximity between land and sea ice before the sea ice breaks up. Continuous access to sea ice allows bears to hunt throughout the year, but in areas where the sea ice melts completely each summer, they are forced to spend several months in tundra fasting on stored fat reserves until freeze-up (Fischlin, et al., 2007).

The two Alaskan populations (Chukchi Sea- ~2,000 individuals in 1993, Southern Beaufort Seas- ~1,500 individuals in 2006) are vulnerable to large-scale dramatic seasonal fluctuations in ice movements because of the associated decreases in abundance and access to prey and increases in the energetic costs of hunting (FWS, 2007). The IPCC projects that with a warming of 2.8°C above pre-industrial temperatures and associated declines in sea ice, polar bears will face a high risk of extinction. Other ice-dependent species (e.g., walruses - for rest; small whales - for protection from predators) face similar consequences, not only in the Arctic but also in the Antarctic (Fischlin, et al., 2007).

In 2005, the World Conservation Union's (IUCN) Polar Bear Specialist Group concluded that the IUCN Red List classification for polar bears should be upgraded from Least Concern to Vulnerable based on the likelihood of an overall decline in the size of the total population of more than 30% within the next 35 to 50 years (Fischlin, et al., 2007). In May 2008, the U.S. Fish and Wildlife Service listed the polar bear as a threatened species under the Endangered Species Act. This decision was based on scientific evidence showing that sea ice loss threatens, and will likely continue to threaten, polar bear habitat (FWS, 2008).

14(b) Ecosystem Services

Ecosystems provide many goods and services that are of vital importance for biosphere function, and provide the basis for the delivery of tangible benefits to humans. These services include: maintenance of biodiversity, nutrient regulation, shoreline protection, food and habitat provisioning, sediment control, carbon sequestration, regulation of the water cycle and water quality, protection of human health, and the production of raw materials (Fischlin et al., 2007). Climate change is projected to have an increasing effect on the provisioning of ecosystem services in the U.S. Increasing temperatures and shifting precipitation patterns, along with the direct effects of elevated CO₂ concentrations, sea level rise, and changes in climatic variability, will affect the quantity and quality of these services. By the end of the 21st century, climate change and its impacts may be the dominant driver of biodiversity loss and changes in ecosystem services globally (Millennium Ecosystem Assessment-Synthesis, 2005).

Many U.S. ecosystems and the services they provide are already threatened by natural and anthropogenic non-climate stressors. Climate-related effects on ecosystems services will amplify the effects of nonclimate stressors. Multiple industries, such as timber, fisheries, travel, tourism, and agriculture that are already threatened could face substantially greater impacts with concurrent effects on financial markets.

14(c) Extreme Events

Many significant impacts of climate change on U.S. ecosystems and wildlife may emerge through changes in the intensity and the frequency of extreme weather events. Extreme events, such as hurricanes, can cause mass mortality in wildlife populations and contribute significantly to alterations in species distribution and abundance following the disturbance. For example, the aftermath of a hurricane can cause coastal forest to die from storm surge-induced salt deposition, or wildlife may find it difficult to

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find food, thus lowering the chance of survival. Droughts play an important role in forest dynamics as well, causing pulses of tree mortality in the North American woodlands. Greater magnitude and frequency of extreme events will alter disturbance regimes in coastal ecosystems leading to changes in diversity and ecosystem functioning. Species inhabiting saltmarshes, mangroves, and coral reefs are likely to be particularly vulnerable to these effects (Fischlin et al., 2007).

14(d) Implications for Tourism and Tribes

The U.S. ranks among the top ten nations for international tourism receipts (US \$112 billion), having domestic tourism and outdoor recreation markets that are several times larger than most other countries. Climate variability affects many segments of this growing economic sector. For example, wildfires in Colorado (2002) caused tens of millions of dollars in tourism losses by reducing visitation and destroying infrastructure. Similar economic losses during that same year were caused by drought-affected water levels in rivers and reservoirs in the western U.S. and parts of the Great Lakes. The ten-day closure and clean-up following Hurricane Georges (September 1998) resulted in tourism revenue losses of approximately US \$32 million in the Florida Keys (Field et al., 2007 and references therein). While the North American tourism industry acknowledges the important influence of climate, its impacts have not been analyzed comprehensively.

In Alaska and elsewhere in the Arctic, indigenous communities are facing major economic and cultural impacts. Many indigenous peoples depend on hunting polar bear, walrus, seals, and caribou, and herding reindeer, fishing and gathering, not only for food and to support the local economy, but also as the basis for cultural and social identity. These livelihoods are already being threatened by multiple climate-related factors, including reduced or displaced populations of marine mammals, caribou, seabirds, and other wildlife, losses of forest resources due to insect damage, and reduced/thinner sea ice, making hunting more difficult and dangerous (ACIA, 2004).

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Section 15

International Impacts

The primary focus of this document is on the observed and potential future impacts associated with elevated GHG concentrations and associated climate change within the U.S. However, EPA has considered the global nature of climate change in at least two ways for purposes of this document.

First, greenhouse gases, once emitted, remain in the atmosphere for decades to centuries, and thus become, for all practical purposes, uniformly mixed in the atmosphere, meaning that U.S. emissions have climatic effects not only in the U.S. but in all parts of the world. Likewise, GHG emissions from other countries can influence the climate of the U.S., and therefore affect the health and/or welfare of the U.S. population. All observed and potential future climate change impacts within the U.S. reviewed in this document consider climate change driven by *global* anthropogenic GHG emissions.

Second, despite widely discussed metrics such as global average temperature, climate change will manifest itself very differently in different parts of the world, where regional changes in temperatures and precipitation patterns, for example, can deviate significantly from changes in the global average. This regional variation in climate change, coupled with the fact that countries are in very different positions with respect to their vulnerability and adaptive capacity, means that the impacts of climate change will be experienced very differently in different parts of the world. In general, the relatively poor nations may experience the most severe impacts, due to their heavier reliance on climate-sensitive sectors such as agriculture and tourism, and due to their lack of resources for increasing resilience and adaptive capacity to climate change (see Parry et al., 2007). In addition to the fact that U.S. GHG emissions may contribute to these impacts (see Section 2 for a comparison of U.S. total and transportation emissions to other countries' emissions), climate change impacts in certain regions of the world may exacerbate problems that raise humanitarian and national security issues for the U.S.

15(a) National Security

The Center for Naval Analyses (CNA) Corporation, a non-profit national security analysis institution, recently issued a report entitled *National Security and the Threat of Climate Change* (2007), in which a dozen retired generals and admirals were briefed by climate change scientists and business leaders over the course of many months and then tasked with providing their own views and recommendations about the linkage between climate change and national security over the next 30 to 40 years. Among their conclusions was that climate change acts as a "threat multiplier" for instability in some of the most volatile regions of the world. "Projected climate change will seriously exacerbate already marginal living standards in many Asian, African, and Middle Eastern nations, causing widespread political instability and the likelihood of failed states," say the authors. Regarding the potential impact of climate change on military systems, infrastructure and operations, the report states that climate change will stress the U.S. military by affecting weapons systems and platforms, bases, and military operations. A U.S. Navy (2001) study is cited which states that an ice-free Arctic will require an increased scope for naval operations. Given these concerns, one of the recommendations of the CNA (2007) report is for the Department of Defense to conduct an assessment of the impact on U.S. military installations worldwide of rising sea levels, extreme weather events, and other possible climate change impacts over the next 30 to 40 years.

The Arctic Climate Impact Assessment (2004) also raised security issues, stating that as Arctic sea ice declines, historically closed sea passages will open, thus raising questions regarding sovereignty over shipping routes and ocean resources. In IPCC (Anisimov, 2007), a study shows projections suggesting that by 2050, the Northern Sea Route will have 125 days per year with less than 75% sea-ice cover, which

represents favorable conditions for navigation by ice-strengthened cargo ships. This may have implications for trade and tourism as well.

The U.S. Congress recently formalized national security concerns due to climate change by requesting that the intelligence community examine these linkages. In March, 2007, Senators Durbin (D-IL) and Hagel (R-NE) introduced the Global Climate Change Security Oversight Act (S. 1018), requiring the Director of National Intelligence (DNI) to submit to Congress a National Intelligence Estimate on the anticipated geopolitical effects of global climate change and the implications of such effects on U.S. national security⁸³.

15(b) Overview of International Impacts

The IPCC Working Group II volume of the Fourth Assessment Report reviews the potential impacts in different regions of the world. The IPCC (Parry et al., 2007) identifies as the most vulnerable regions:

• The Arctic, because of high rates of projected warming on natural systems;

 • Africa, especially the sub-Saharan region, because of current low adaptive capacity as well as climate change;

 Small islands, due to high exposure of population and infrastructure to risk of sea-level rise and increased storm surge;

 • Asian mega deltas, such as the Ganges-Brahmaputra and the Zhujiang, due to large populations and high exposure to sea level rise, storm surge and river flooding.

Table 15.1 summarizes the vulnerabilities and projected impacts for different regions of the world, as identified by IPCC (2007b). And the paragraphs that follow provide some additional detail for key sectoral impacts that have received attention by the research community. There is currently a lack of information about how these potential impacts in other regions of the world may influence international trade and migration patterns, which in turn could raise concerns for the U.S.

 On a global basis, according to IPCC, "projected climate change-related exposures are likely to affect the health status of millions of people, particularly those with low adaptive capacity," through several factors including "the increased frequency of cardio-respiratory diseases due to higher concentrations of ground level ozone related to climate change (IPCC, 2007b)." More specifically, "cities that currently experience heat waves are expected to be further challenged by an increased number, intensity and duration of heat waves during the course of the century, with potential for adverse health impacts."

Mosquito-borne diseases which are sensitive to climate change, such as dengue and malaria are of great importance globally. Studies have reported associations between spatial (Hales et al., 2002), temporal (Hales et al., 1999; Corwin et al., 2001; Gagnon et al., 2001), or spatiotemporal patterns (Hales et al., 1999; Corwin et al., 2001; Gagnon et al., 2001; Cazelles et al., 2005) of dengue and climate, although these are not entirely consistent (Confalonieri et al., 2007). Similarly, the spatial distribution, intensity of transmission, and seasonality of malaria is observed to be influenced by climate in sub-Saharan Africa (Hay et al., 2002a; Craig et al., 2004 in Confalonieri et al., 2007). In other world regions (e.g., South America, continental regions of the Russian Federation) there is no clear evidence that malaria has been affected by climate change (Benitez et al., 2004; Semenov et al., 2002 in Confalonieri et al., 2007).

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⁸³ For further information on S. 1018 see: http://thomas.loc.gov/cgi-bin/bdquery/z?d110:s1018: Likewise, in May, 2007, the House of Representatives amended and passed the Intelligence Authorization Act for Fiscal Year 2008 (H.R. 2082), which also requires the DNI to submit to Congress a national intelligence estimate on anticipated geopolitical effects of global climate change and its implications on U.S. national security. For further information on H.R. 2082 see: http://thomas.loc.gov/cgi-bin/bdquery/z?d110:h.r.02082:

Changes in reporting, surveillance, disease control measures, population changes and other factors such as land use change must to be taken into account when attempting to attribute changes in human diseases to climate change (Kovats et al., 2001; Rogers and Randolph, 2006 in Confalonieri et al., 2007).

Food production is expected to be much more vulnerable to climate change in poorer regions of the world compared to food production in the U.S. and other high, northern latitude regions. The IPCC (2007b) stated with medium confidence⁸⁴ that, at lower latitudes, especially seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1-2°C; ~2-3.5°F), which would increase risk of hunger. Furthermore, increases in the frequency of droughts and floods are projected to affect local production negatively, especially in subsistence sectors at low latitudes. Drought conditions, flooding, and pest outbreaks are some of the current stressors to food security that may be influenced by future climate change. Sub-Saharan Africa is currently highly vulnerable to food insecurity (Easterling et al., 2007). Felzer et al. (2005) projected increases in carbon storage on croplands globally under climate change up to 2100, but found that ozone damage to crops could significantly offset these gains.

Regarding global forest production, the IPCC (Easterling et al., 2007) concluded that forestry production is estimated to change modestly with climate change in the short and medium term (medium confidence). The projected change in global forest products output ranges from a modest increase to a slight decrease, with significant variations regionally. There is projected to be a production shift from low latitude regions in the short-term, to high latitude regions in the long-term. Projected changes in the frequency and severity of extreme climate events have significant consequences for forestry production in addition to impacts of projected mean climate (high confidence) (Easterling et al., 2007). Climate variability and change also modify the risks of fires, and pest and pathogen outbreaks, with negative consequences for forestry (high confidence) (Easterling et al., 2007).

The IPCC recently made the following conclusions when considering how climate change may affect water resources across all world regions:

- The impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, sea level, and precipitation variability (very high confidence) (Kundzewicz et al. 2007).
- All regions show an overall net negative impact of climate change on water resources and freshwater ecosystems (high confidence). Areas in which runoff is projected to decline are likely to face a reduction in the value of the services provided by water resources (very high confidence). The beneficial impacts of increased annual runoff in other areas will be tempered by negative effects due to increased precipitation variability and seasonal runoff shifts on water supply, water quality, and flood risk (high confidence) (Kundzewicz et al., 2007).
- Climate change affects the function and operation of existing water infrastructure as well as water management practices. Adverse effects of climate change on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land use change, and urbanization. Globally, water demand will grow in the coming decades, primarily due to population growth and increased affluence; regionally, large changes in irrigation water demand as a result of climate changes are likely. Current water management practices are very likely to be inadequate to reduce negative impacts of climate change on water supply reliability, flood risk, health, energy, and aquatic ecosystems (very high confidence) (Kundzewicz et al., 2007).

⁸⁴ According to IPCC terminology, "medium confidence" conveys a 5 out of 10 chance of being correct. See Box 1.3 on page 5 for a full description of IPCC's uncertainty terms.

• In polar regions, components of the terrestrial cryosphere and hydrology are increasingly being affected by climate change. Changes to cryospheric processes⁸⁵ are also modifying seasonal runoff (very high confidence) (Anisimov et al., 2007).

The IPCC (Nicholls et al., 2007) identified that coasts are experiencing the adverse consequences of hazards related to climate and sea level (very high confidence). They are highly vulnerable to extreme events, such as storms which impose substantial costs on coastal societies. Through the 20th century, global rise of sea level contributed to increased coastal inundation, erosion, and ecosystem losses, but with considerable local and regional variation due to other factors (Nicholls et al., 2007).

The IPCC (Fischlin et al., 2007) recently made the following conclusions when considering how climate change may affect ecosystems across all world regions:

- During the course of this century the resilience of many ecosystems is likely to be exceeded by an unprecedented combination of changes in climate and in other global change drivers (especially land use, pollution, and overexploitation), if greenhouse gas emissions and other changes continue at or above current rates (high confidence). The elevated CO₂ levels and associated climatic changes will alter ecosystem structure, reduce biodiversity, perturb functioning of most ecosystems, and compromise the services they currently provide (high confidence). Present and future land use change and associated landscape fragmentation are very likely to impede species' migrations and geographic range shifts in response to changes in climate (very high confidence).
- Ecosystems and species are very likely to show a wide range of vulnerabilities to climate change, depending on the extent to which climate change alters conditions that could cross critical, ecosystem-specific thresholds (very high confidence). The most vulnerable ecosystems include coral reefs, the sea ice biome and other high latitude ecosystems (e.g. boreal forests), mountain ecosystems and Mediterranean-climate ecosystems (high confidence). Least vulnerable ecosystems include savannas and species—poor deserts, but this assessment is especially subject to uncertainty relating to the CO₂ fertilization effect and disturbance regimes such as fire (low confidence).

Table 15.1: Examples of key regional impacts as identified by IPCC (2007b)

Africa

- New studies confirm that Africa is one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity. Some adaptation to current climate variability is taking place; however, this may be insufficient for future changes in climate.
- By 2020, between 75 million and 250 million people are projected to be exposed to increased water stress due to climate change. If coupled with increased demand, this will adversely affect livelihoods and exacerbate water-related problems.
- Agricultural production, including access to food, in many countries and regions is projected
 to be severely compromised by climate variability and change. The area suitable for
 agriculture, the length of growing seasons and yield potential, particularly along the margins
 of semi-arid and arid areas, are expected to decrease. This would further adversely affect
 food security and exacerbate malnutrition in the continent. In some countries, yields from
 rain-fed agriculture could be reduced by up to 50% by 2020.

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⁸⁵ Cryospheric processes are defined to include the annual freezing and melting of snow cover, ice sheets, lake and river ice, permafrost, and sea ice.

⁸⁶ Mediterranean climate ecosystems feature subtropical climate with dry summers. Despite the name, these ecosystems exist in the US along the coasts of central and southern California.

Asia

- Glacier melt in the Himalayas is projected to increase flooding, and rock avalanches from destabilized slopes, and to affect water resources within the next two to three decades. This will be followed by decreased river flows as the glaciers recede.
- Freshwater availability in Central, South, East and South-East Asia, particularly in large river basins, is projected to decrease due to climate change which, along with population growth and increasing demand arising from higher standards of living, could adversely affect more than a billion people by the 2050s.
- Coastal areas, especially heavily-populated mega delta regions in South, East and South-East Asia, will be at greatest risk due to increased flooding from the sea and, in some mega deltas, flooding from the rivers.
- It is projected that crop yields could increase up to 20% in East and South-East Asia while
 they could decrease up to 30% in Central and South Asia by the mid-21st century. The risk
 of hunger is projected to remain very high in several developing countries.
- Endemic morbidity and mortality due to diarrhea disease primarily associated with floods and droughts are expected to rise in East, South and South-East Asia due to projected changes in the hydrological cycle associated with global warming. Increases in coastal water temperature would exacerbate the abundance and/or toxicity of cholera in South Asia.

Latin America

- By mid-century, increases in temperature and associated decreases in soil water are
 projected to lead to gradual replacement of tropical forest by savanna in eastern Amazonia.
 Semi-arid vegetation will tend to be replaced by arid-land vegetation. There is a risk of
 significant biodiversity loss through species extinction in many areas of tropical Latin
 America.
- In drier areas, climate change is expected to lead to salinization and desertification of agricultural land. Productivity of some important crops is projected to decrease and livestock productivity to decline, with adverse consequences for food security. In temperate zones soybean yields are projected to increase.
- Sea-level rise is projected to cause increased risk of flooding in low-lying areas. Increases in sea surface temperature due to climate change are projected to have adverse effects on Mesoamerican coral reefs, and cause shifts in the location of south-east Pacific fish stocks.
- Changes in precipitation patterns and the disappearance of glaciers are projected to significantly affect water availability for human consumption, agriculture and energy generation.

Polar Regions

- For human communities in the Arctic, impacts, particularly those resulting from changing snow and ice conditions, are projected to be mixed. Detrimental impacts would include those on infrastructure and traditional indigenous ways of life.
- Beneficial impacts would include reduced heating costs and more navigable northern sea routes.

Small Islands

- Small islands, whether located in the tropics or higher latitudes, have characteristics which make them especially vulnerable to the effects of climate change, sea-level rise and extreme events.
- Deterioration in coastal conditions, for example through erosion of beaches and coral bleaching, is expected to affect local resources, e.g., fisheries, and reduce the value of these destinations for tourism.
- Sea-level rise is expected to exacerbate inundation, storm surge, erosion and other coastal hazards, thus threatening vital infrastructure, settlements and facilities that support the livelihood of island communities.
- · Climate change is projected by mid-century to reduce water resources in many small

islands, e.g., in the Caribbean and Pacific, to the point where they become insufficient to meet demand during low-rainfall periods.

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^{*} With the exception of some very high confidence statements for small islands, all other IPCC conclusions within the table are of either high or medium confidence.

Appendix: Brief Overview of Adaptation

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Introduction

Adaptation to climate change is the adjustment in the behavior or nature of a system to the effects of climate change. In the process of developing information to support the Administrator's decision regarding whether elevated combined greenhouse gas (GHG) concentrations endanger public health or

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welfare, various questions were raised about the relevance of adaptation. This document provides a preliminary review of the state of knowledge pertaining to adaptation.

What is Adaptation?

As defined in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007),

Adaptation to climate change takes place through adjustments to reduce vulnerability or enhance resilience in response to observed or expected changes in climate and associated extreme weather events. Adaptation occurs in physical, ecological and human systems. It involves changes in social and environmental processes, perceptions of climate risk, practices and functions to reduce potential damages or to realise new opportunities.

Adaptations vary according to the system in which they occur, who undertakes them, the climatic stimuli that prompts them, and their timing, functions, forms and effects. Adaptation can be of two broad types:

- Reactive or autonomous adaptation is the process by which species and ecosystems respond to changed conditions. An example is the northward migration of a species in response to increasing temperature.
- Anticipatory adaptation is planned and implemented before impacts of climate change are observed. An example is the construction of dikes in response to (and to prepare for) expected sea level rise.

Summary of the Scientific Literature on Adaptation

- 1. There is experience with adapting to weather, climate variability and the current and projected impacts of climate change.
 - There is a long record of practices to adapt to the impacts of weather as well as natural climate variability. These practices include proactive steps like water storage and crop and livelihood diversification, as well as reactive or ex-post steps like emergency response, disaster recovery and migration.⁸⁷
 - o The IPCC (2007) states with very high confidence 88 that "Adaptation to climate change is already taking place, but on a limited basis."89

Very high confidence High confidence

At least 9 out of 10 chance of being correct About 8 out of 10 chance

⁸⁷ Adger et al. (2007), p. 720

⁸⁸ A set of terms to describe uncertainties in current knowledge was used throughout IPCC's Fourth Assessment Report. On the basis of a comprehensive reading of the literature and their expert judgment, IPCC authors assigned a confidence level to major statements on the basis of their assessment of current knowledge, as follows:

- O A wide array of adaptation options is available, ranging from purely technological (i.e., sea walls), through behavioral changes (i.e., altered food and recreational choices), to managerial (e.g. altered farm practices), and to policy (e.g. planning regulations). 90
- 2. Although adaptation options are known, available and used in some places, there are significant barriers to their adoption.
 - O The IPCC states -- with very high confidence -- that "there are substantial limits and barriers to adaptation." These include formidable environmental, economic, informational, social, attitudinal and behavioral barriers to the implementation of adaptation that are not fully understood. The IPCC also states that there are significant knowledge gaps for adaptation as well as impediments to flows of knowledge and information relevant to adaptation decisions. See that there are significant as well as impediments to flows of knowledge and information relevant to adaptation decisions.
- 3. Current scientific information does not provide sufficient information to assess how effective current and future adaptation options will be at reducing vulnerability to the impacts of climate change. The fact that a country has a high capacity to adapt to climate change does not mean that its actions will be effective at reducing vulnerability.
 - O While most technologies and strategies are known and developed in some countries, the available scientific literature does not indicate how effective various options are at fully reducing risks, particularly at higher levels of warming and related impacts, and for vulnerable groups.⁹³
 - O High adaptive capacity does not necessarily translate into actions that reduce vulnerability. For example, despite a high capacity to adapt to heat stress through relatively inexpensive adaptations, residents in urban areas in some parts of the world, including European cities, continue to experience high levels of mortality. For similar reasons, EPA has worked collaboratively with other government agencies to provide guidance to municipalities on steps they can take to reduce heat-related morbidity and mortality. 95
 - o Further research is needed to monitor progress on adaptation, and to assess the direct as well as ancillary effects of adaptation measures. ⁹⁶ (IPCC, Chapter 17, p. 33)
- 4. For any country even one with high adaptive capacity -- it is particularly difficult to reduce vulnerability for all segments of the population. The most vulnerable and difficult to reach populations are the elderly, children and the poor.

Medium confidence Low confidence Very low confidence About 5 out of 10 chance About 2 out of 10 chance Less than a 1 out of 10 chance

⁸⁹Adger et al. (2007), p. 720

⁹⁰ ibid

⁹¹ ibid

⁹² Adger et al. (2007), p. 719

⁹³ ibid

⁹⁴ ibid

⁹⁵ Excessive Heat Events Guidebook (2006)

⁹⁶ Adger et al. (2007) p. 737

- O The IPCC states with very high confidence that "adaptive capacity is uneven across and within societies." There are individuals and groups within all societies that have insufficient capacity to adapt to climate change. 97
- 5. More adaptation will be required to reduce vulnerability to climate change. ⁹⁸ Additional adaptation can potentially reduce, but is never expected to completely eliminate vulnerability to current and future climate change.
 - O According to the IPCC, "adaptation alone is not expected to cope with all the projected effects of climate change, and especially not over the long term as most impacts increase in magnitude." ⁹⁹
- 6. A portfolio of adaptation and mitigation measures can diminish the risks associated with climate change.
 - Even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes adaptation essential, particularly in addressing near-term impacts. Unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt.

⁹⁷ Adger et al. (2007), p. 719 98 Adger et al. (2007), p. 719

 ⁹⁸ Adger et al. (2007), p. 719
 99 IPCC (2007), p. 19

¹⁰⁰ IPCC (2007), p. 19

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